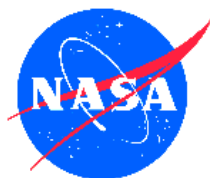




# **Creep, Fatigue and Fracture Behavior of Environmental Barrier Coating and SiC-SiC Ceramic Matrix Composite Systems: The Role of Environment Effects**

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**The 11th International Conference on Ceramic Materials and Components for Energy and Environmental Applications**  
**Vancouver, British Columbia, Canada**  
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# Durable Environmental Barrier Coating Systems for Ceramic Matrix Composites (CMCs):

Enabling Technology for Next Generation Low Emission, High Efficiency and Light-Weight Propulsion



## — NASA Environmental barrier coatings (EBCs) development objectives

- Help achieve future engine temperature and performance goals
- Ensure system durability – towards prime reliant coatings
- Establish database, design tools and coating lifing methodologies
- Improve technology readiness



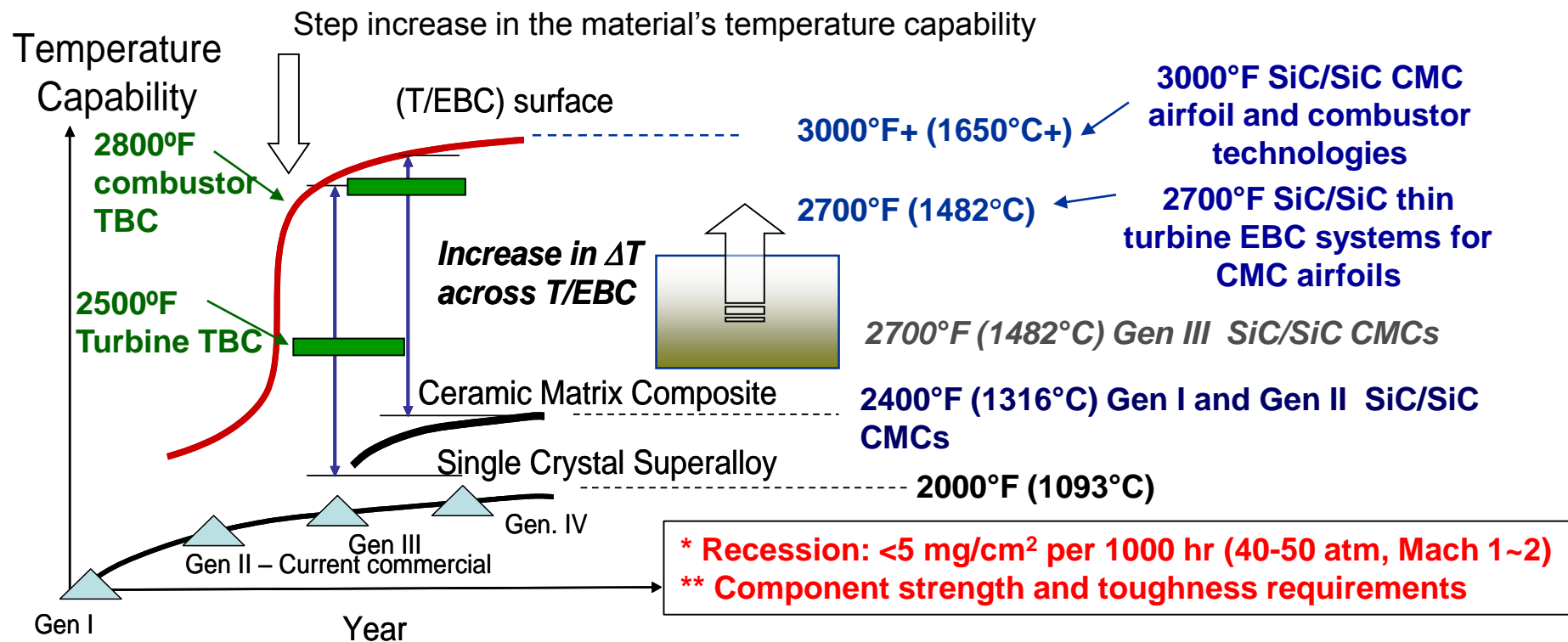
Fix Wing Subsonic Aircraft



Supersonics Aircraft

## NASA Environmental Barrier Coating Development Goals

- Emphasize temperature capability, performance and durability
- Develop innovative coating technologies and life prediction approaches
- 2700°F (1482°C) EBC bond coat technology for supporting next generation
- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
  - Meet 1000 hr for subsonic aircraft and 9,000 hr for supersonics/high speed aircraft hot-time life requirements





## Outline

- **Environmental barrier coating system development: challenges and limitations**
- **Advanced environmental barrier coating systems (EBCs) for CMC airfoils and combustors**
  - NASA EBC systems and material system evolutions
  - Current turbine and combustor EBC coating emphases
  - Advanced EBC development: processing, testing and durability
- **Design tool and life prediction perspectives of coated CMC components**
- **Advanced CMC-EBC rig demonstrations**
- **Summary and future directions**

## Fundamental Recession Issues of CMCs and EBCs

### - Recession of Si-based Ceramics

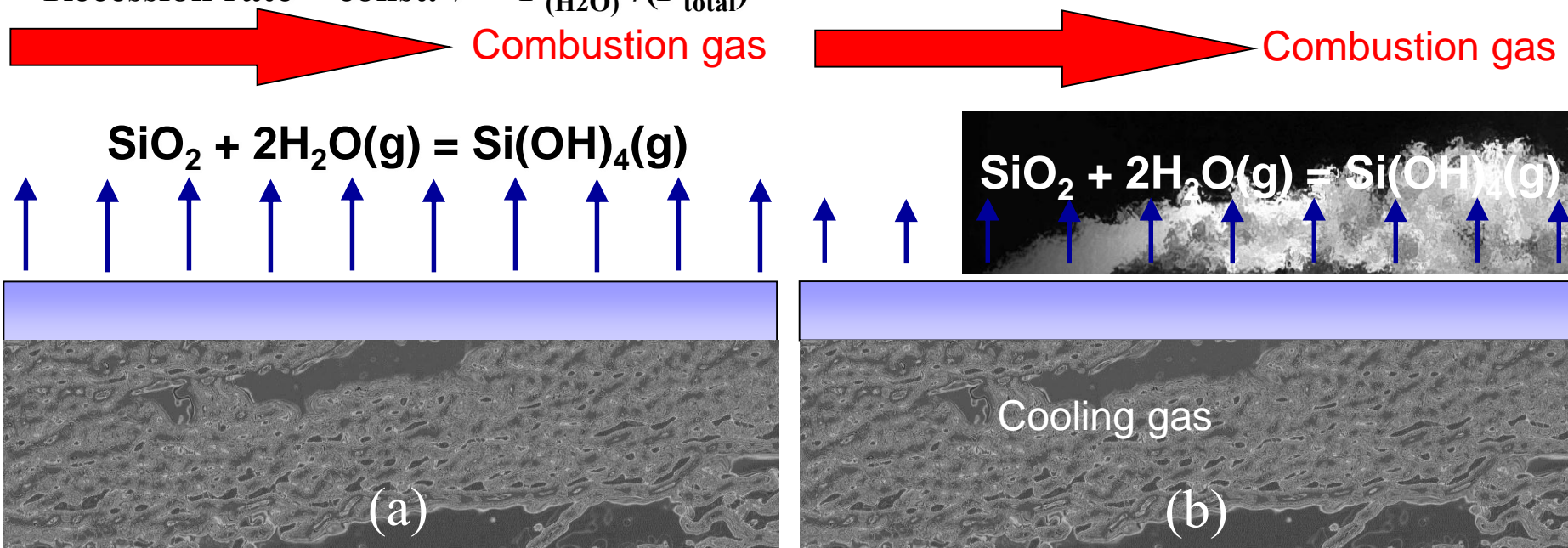
(a) Convective; (b) Convective with film-cooling

- Low  $\text{SiO}_2$  activity EBC system development emphasis

### - Advanced rig testing and modeling

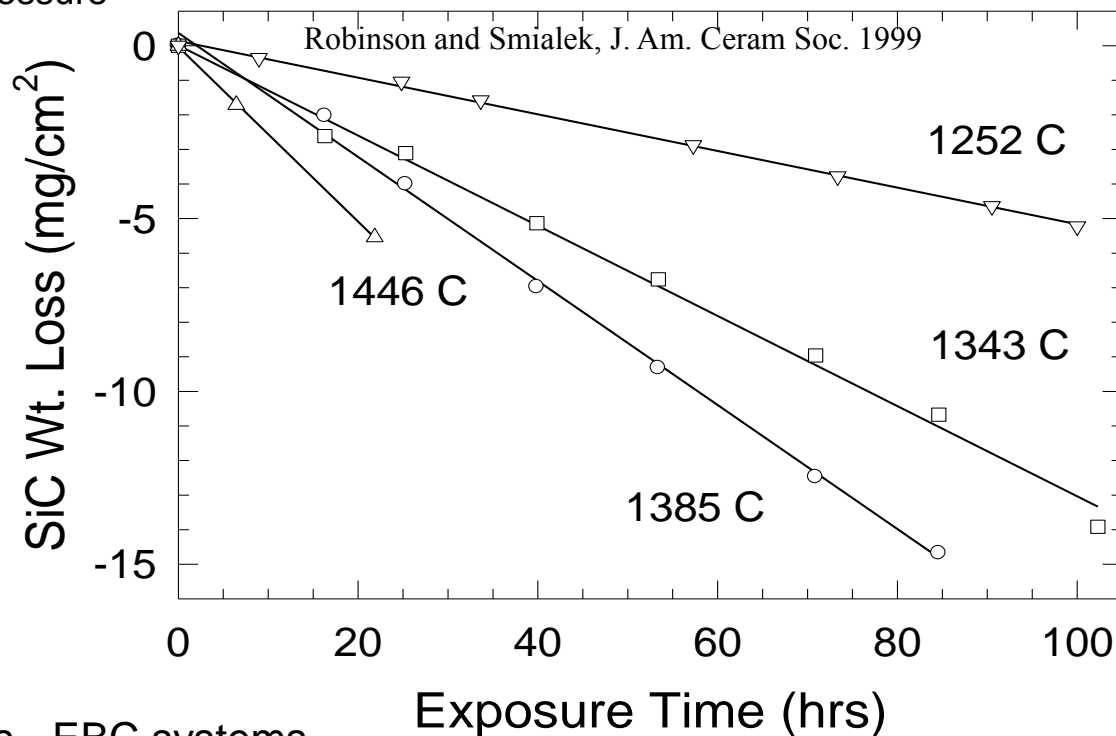
More complex recession behavior of CMC and EBCs in High Pressure Burner Rig

$$\text{Recession rate} = \text{const. } V^{1/2} P_{(\text{H}_2\text{O})}^2 / (P_{\text{total}})^{1/2}$$

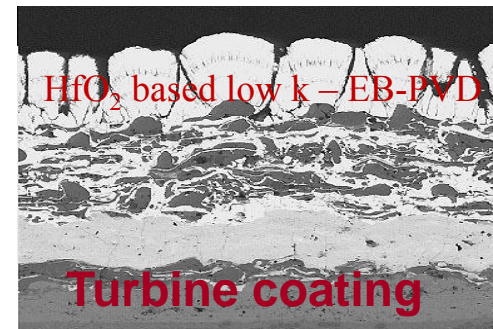
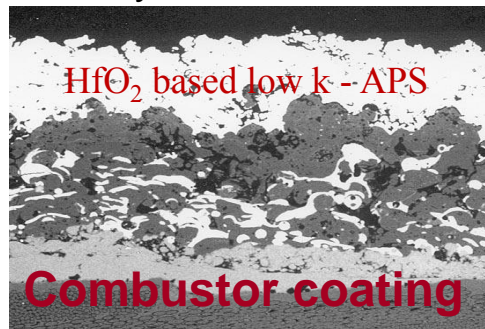
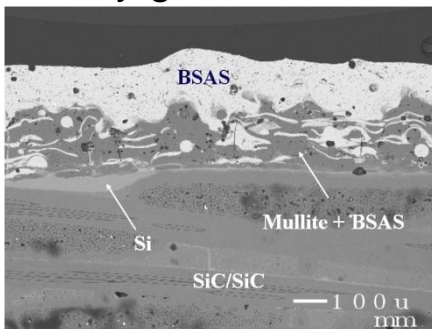


# Fundamental Recession Issues of CMCs and EBCs - Continued

Weight Loss of SiC in High Pressure Burner Rig  
6 atm 20 m/s



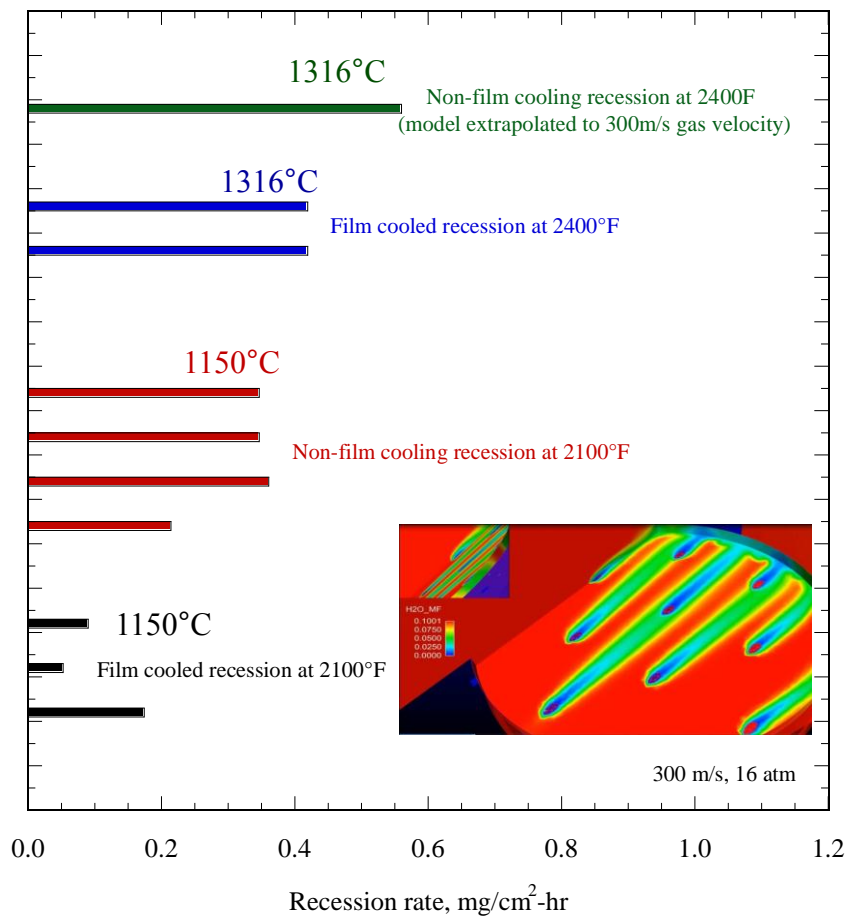
- Early generation coatings - EBC systems



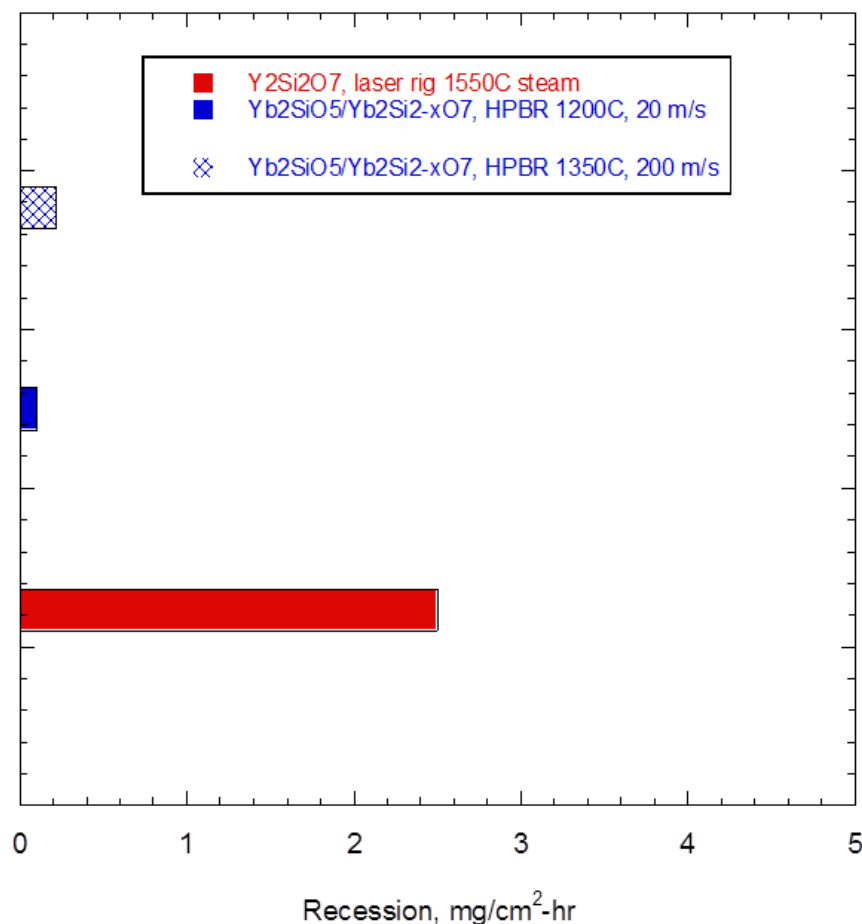


# SiC/SiC CMC and EBC Recession Kinetics Determined for CMCs-EBCs in High Pressure Bruner Rig and Laser Steam Rig Testing

— Determined recession under complex, and realistic simulated turbine conditions



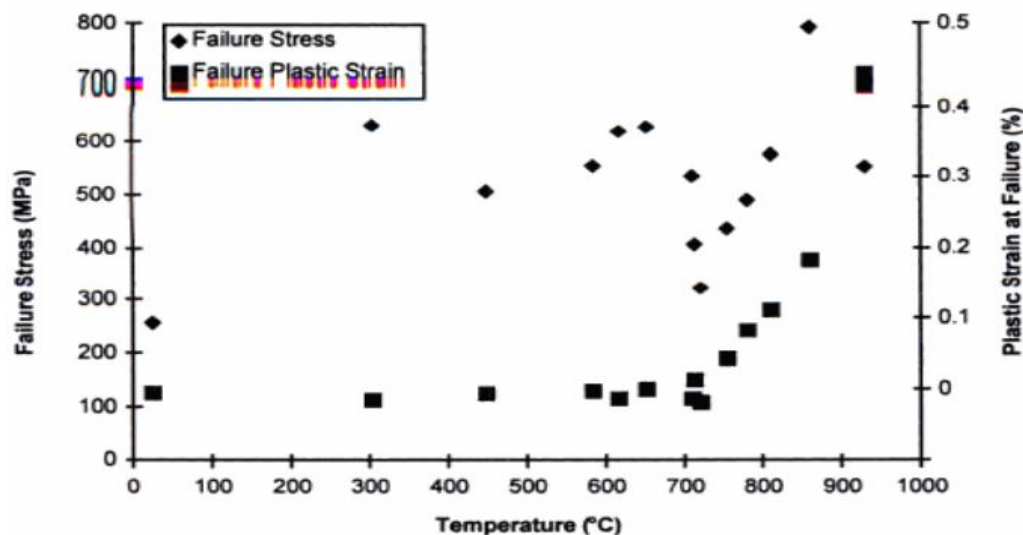
High temperature recession kinetics for film-cooled and non-film cooled Gen II SiC/SiC CMCs



Examples of environmental barrier coating recession in laboratory simulated turbine engine conditions

## Degradation Mechanisms for Si Bond Coat

- Silicon bond coat melts at 1410°C (melting point)
- Fast oxidation rates (forming  $\text{SiO}_2$ ) and high volatility at high temperature
- Low toughness at room temperature ( $0.8\text{-}0.9 \text{ MPa m}^{1/2}$ ; Brittle to Ductile Transition Temperature about 750°C)
- Low strength and high creep rates at high temperatures, leading to coating delamination
- Interface reactions leading to low melting phases
  - A more significant issue when sand deposit Calcium- Magnesium – Alumino-Silicate (CMAS) is present
- Si and  $\text{SiO}_2$  volatility at high temperature (with and without moisture)

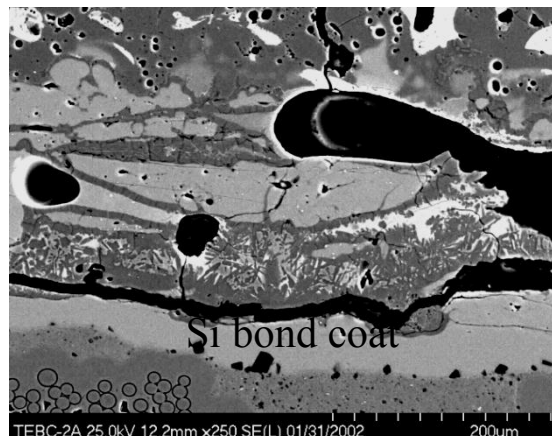
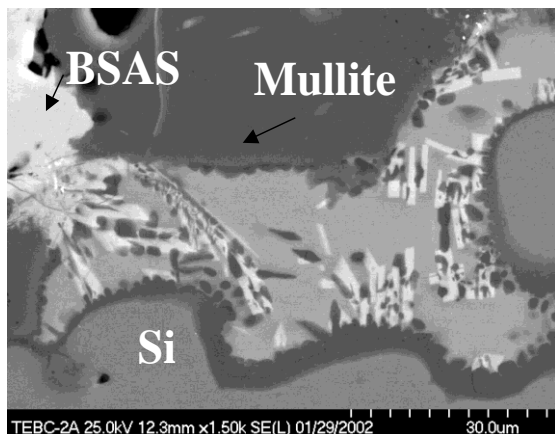


Brittle to Ductile transition in polycrystalline Si

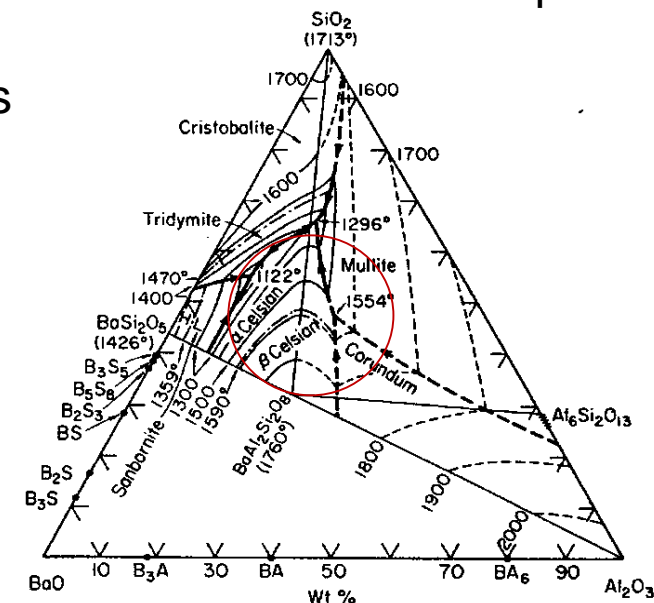


## Degradation Mechanisms for Si Bond Coat – Interface reactions

- Significant interfacial pores and eutectic phases formation due to the water vapor attack and Si diffusion at 1300°C
- Heat flux condition further limit the use temperatures



SEM images Interface reactions at 1300°C; total 200 hot hours



BaO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> ternary phase diagram



Interface Si bond coat melting of selected coating systems, under laser heat flux tests, 1" dia button specimen



Si bond coat after 1350°C, 50 hr furnace test in air; 1" dia plasma sprayed EBC button specimen



Hot pressed BSAS+Si button specimen after 1350°C, 50 hr furnace test in air

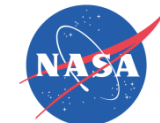
# Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art



## – Advanced EBC system developments

	Gen I (EPM) 1995-2000 R&D Award	Gen II (UEET) 2000-2004	Gen III (UEET) 2000-2005 R&D Award (2007)	Gen IV (FAP) 2005-2011 R&D Award (2007) coating turbine development	Gen V-VI (FAP - ERA) 2007 – 2012 to present	Gen VII (FAP) 2009 – present Patent 13/923,450 PCT/US13/46946
Engine Components:	Combustor	Combustor/ (Vane)	Combustor/ Vane	Vane/ Blade	- Vane/Blade EBCs - Equivalent APS combustor EBCs	Airfoil components
Top Coat:	BSAS (APS)	RE <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> or RE <sub>2</sub> SiO <sub>5</sub> (APS)	- (Hf, Yb, Gd, Y) <sub>2</sub> O <sub>3</sub> - ZrO <sub>2</sub> /HfO <sub>2</sub> +RE silicates - ZrO <sub>2</sub> /HfO <sub>2</sub> +BSAS (APS and EBPVD)	RE-HfO <sub>2</sub> -Alumino silicate  (APS and/or 100% EB- PVD)	RE-HfO <sub>2</sub> -X advanced top coat RE-HfO <sub>2</sub> -graded Silica (EB-PVD)	Advanced EBC
Interlayer:	--	--	RE-HfO <sub>2</sub> /ZrO <sub>2</sub> - aluminosilicate layered systems	Nanocomposite graded oxide/silicate	Gen IV interlayer not required (optional)	
EBC:	Mullite+ BSAS	BSAS+Mullite	RE silicates or RE-Hf mullite	RE doped mullite-HfO <sub>2</sub> or RE silicates	Multi-component RE silicate systems	Multicomponent RE-silicate /self grown
Bond Coat:	Si	Si	Oxide+Si bond coat	HfO <sub>2</sub> -Si-X, doped mullite/Si SiC nanotube	Optimized Gen IV HfO <sub>2</sub> -Si-X bond coat 2700°F bond coats	RE-Si+X systems
Thickness	10-15 mil	10-15 mil	15-20 mil	10 mil	5 mil	1 -3 mils
Surface T:	Up to 2400°F	2400°F	3000°F/2400CMC	2700°F/2400F CMC	3000°F	
Bond Coat Challenges overcome by advancements:	Limit to 2462°F improved phase stability, recession resistance of top coat	Limit to 2642°F Increased phase stability and toughness	Proven at 2600°F +; Advancements targeting 2700°F	Advanced compositions & processing for thinner coatings, higher stability and increased toughness		

# Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art - Continued



## — Major development milestones:

- 1995-2000: BSAS/Mullite+BSAS/Si
- 2000-2004: **RE<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>** or RE<sub>2</sub>SiO<sub>5</sub>/BSAS+Mullite/Si
- 2000-2004 - 3000°F EBC systems: HfO<sub>2</sub> systems (**HfO<sub>2</sub> version four-component low k**) / RE<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> or RE<sub>2</sub>SiO<sub>5</sub> / BSAS+Mullite/Si and **Oxide+Si** bond coats; component demonstrations
  - *Modified mullite (with transition metal and RE dopants) to replace BSAS+mullite*
  - *Many compound oxide top coat materials explored*
- 2005-2011 - Turbine coating systems: Multi-component, graded HfO<sub>2</sub>-Rare Earth Oxide-SiO<sub>2</sub>/ multi-component Rare earth Silicate/ HfO<sub>2</sub>-Si systems
  - **RE-HfO<sub>2</sub>-X/Multicomponent RE-silicate / HfO<sub>2</sub>-Si +X** (doped)
- 2009-present: **Improved EBC compositions** in progress; **RE-Si bond coat**
  - **(Gd,Yb,Y)Si bond coat and top coat**

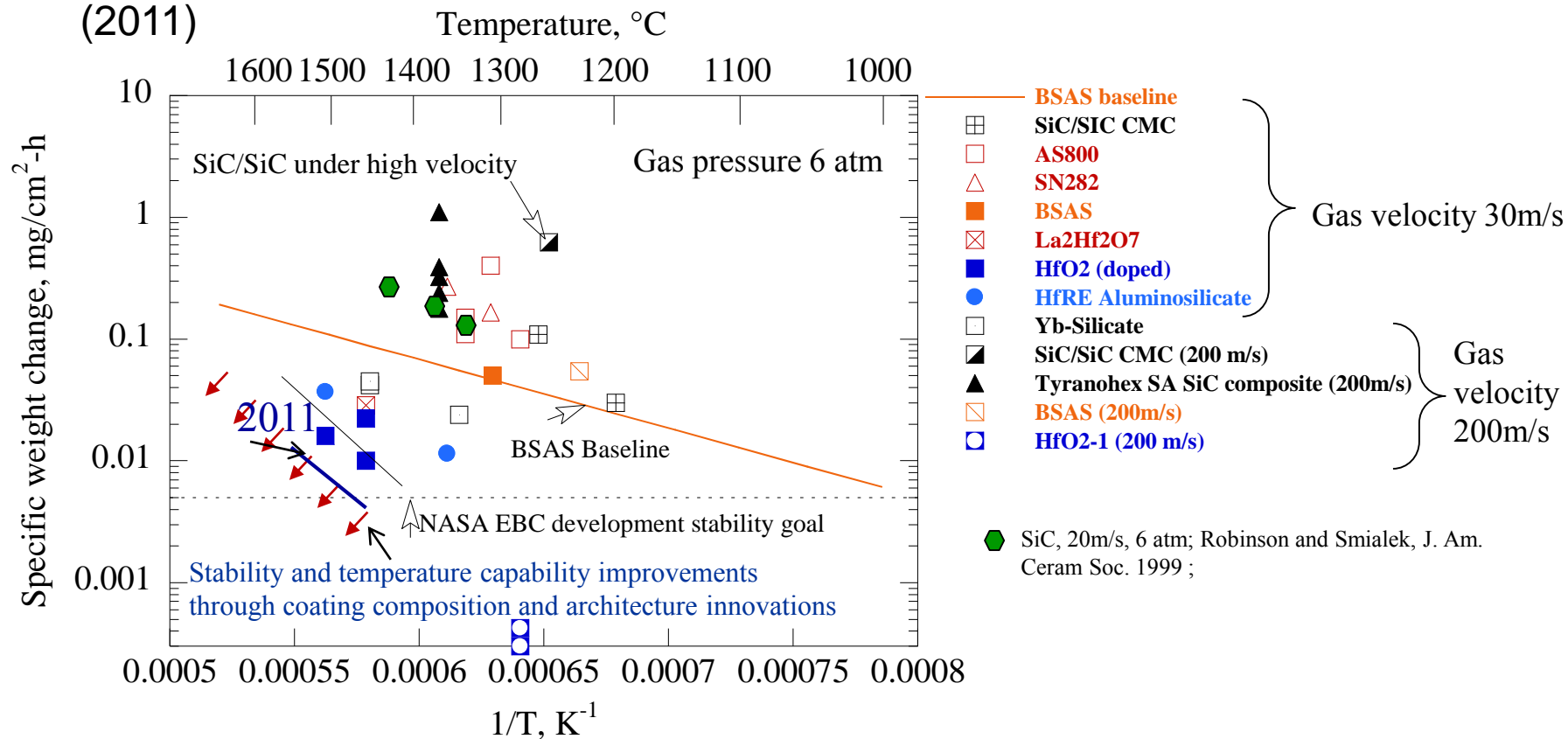


## **NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art - Continued**

- Develop processing capabilities, experience and demonstrate feasibilities in various techniques: air plasma spray, Electron Beam - Physical Vapor Deposition (EB-PVD), Plasma Sprayed-Physical Vapor Deposition (PS-PVD):
  - Efforts in developing turbine EBC coatings with Directed Vapor Technologies using Directed Vapor EB-PVD: Turbine Airfoils
  - In-house APS, and Triplex Pro APS (with Sulzer/Oerlikon Metco) - for Combustor applications
  - Cathodic arc and Magnetron PVD processes: bond coat developments
  - In-house PS-PVD
  - Some planned EBCs DVM/DVC coatings (with Praxair): aiming at combustor EBC

# Environmental Stability of Selected Environmental Barrier Coatings Demonstrated in NASA High Pressure Burner Rig

- EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment
- Advanced EBC recession met NASA Fundamental Aeronautics Project goals (2011)

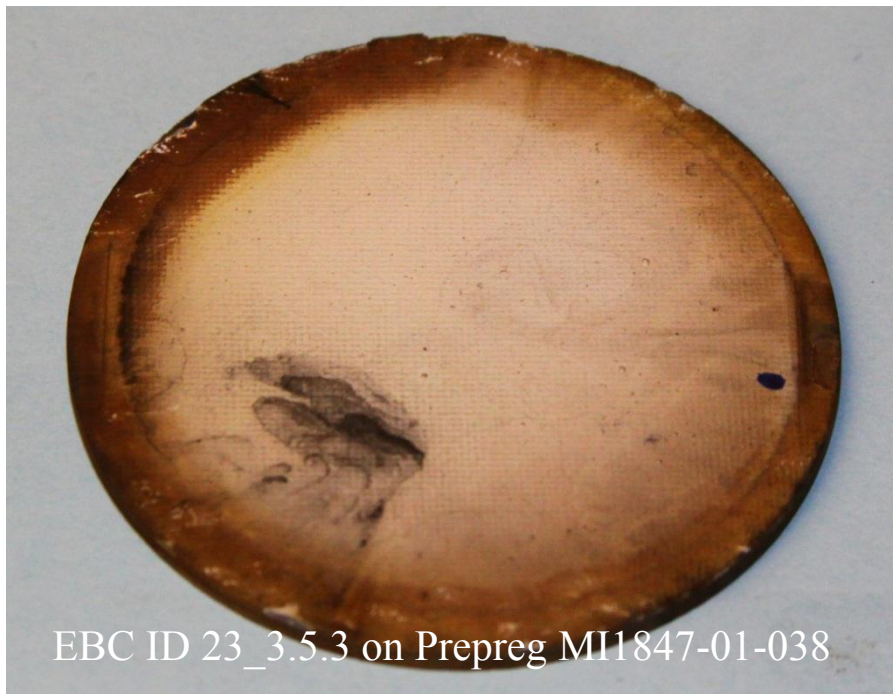


Stability of selected coatings systems

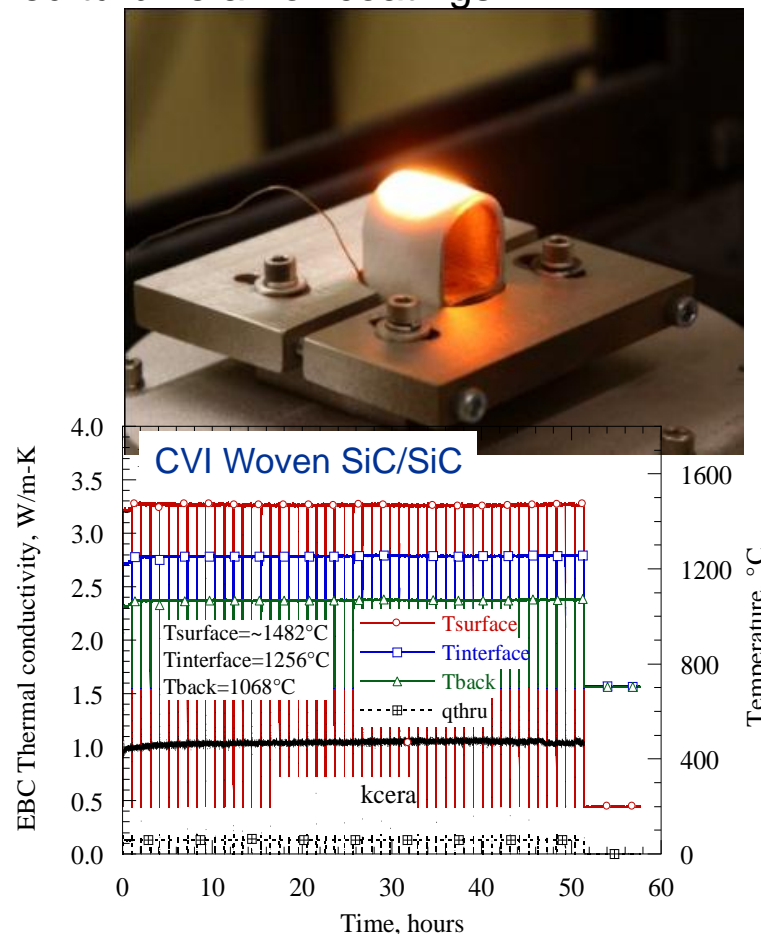


## NASA Turbine Environmental Barrier Coating Developments - Continued

- Advanced EBC top coats tested in coupons under laser heat flux cyclic rigs up 1700°C
- Coated subelements coating tested up 1500°C under laser thermal gradient for 200 hr
- EBC systems show high stability in High Pressure Burner Rig Tests
- Low thermal conductivity of 1.2 W/m-K for optimized turbine airfoil coatings



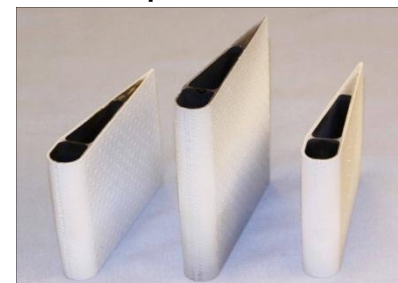
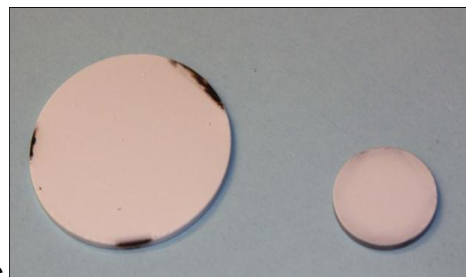
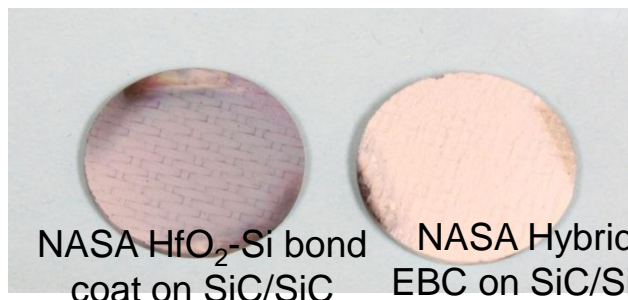
High pressure burner rig, 16 atm, 31 hr –  
no measureable weight loss



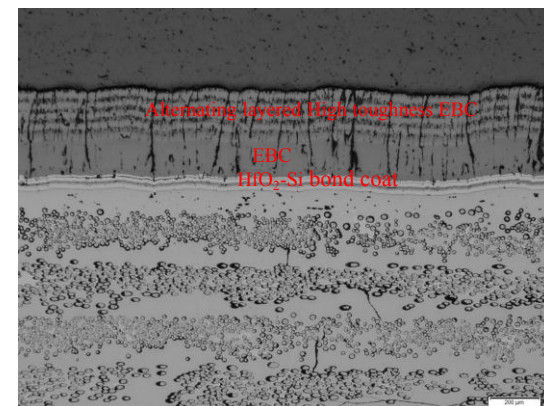
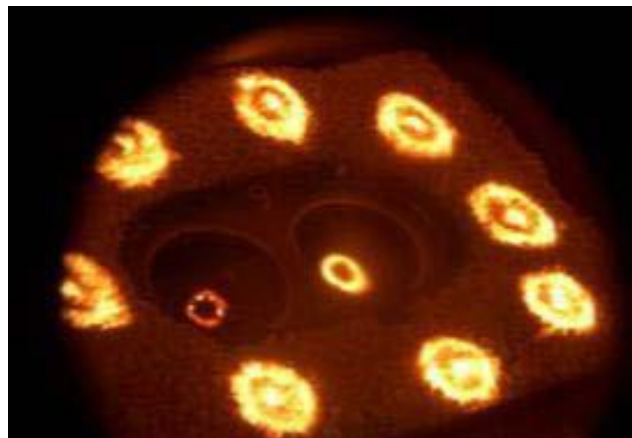
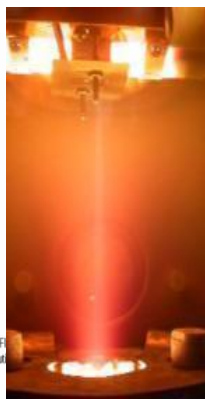
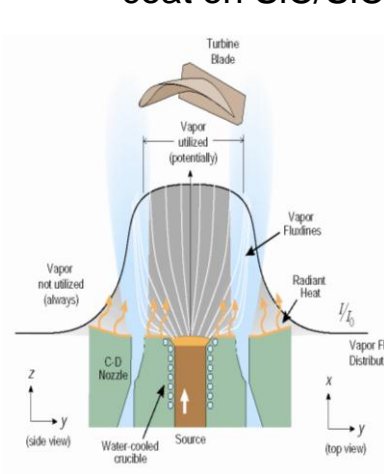


# Development and Processing of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD)

- NASA programs in supporting processing developments and improvements with Directed Vapor Technologies International, Inc.
  - Multicomponent thermal and environmental barrier coating vapor processing developments
  - High toughness turbine coatings
  - Affordable manufacture of environmental barrier coatings for turbine components



Advanced multi-component and multilayer turbine EBC systems

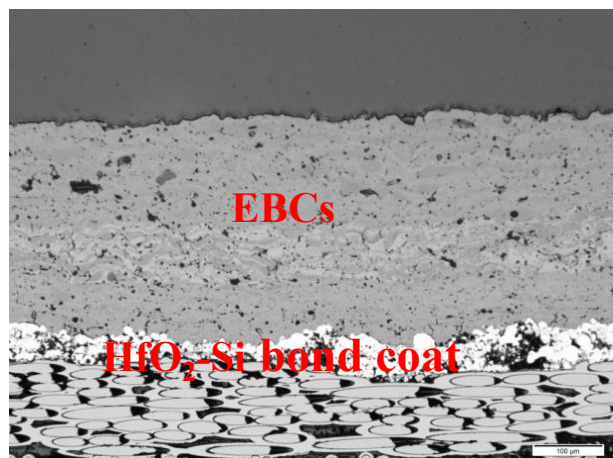


Directed Vapor Processing systems

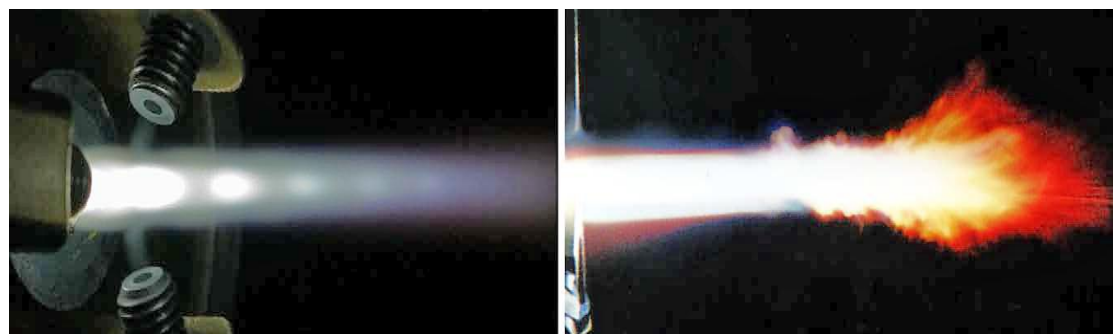
Processed EBC system

# Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

- Focused on advanced composition and processing developments using state-of-the-art techniques
- Improved processing envelopes using high power and higher velocity, graded systems processing for advanced TEBCs and thermal protection systems



NASA EBC processed by Triplax pro



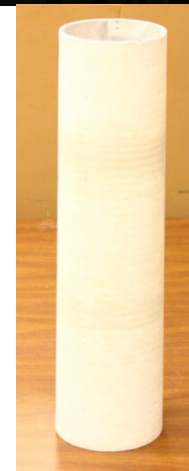
Sulzer Triplex Pro system having high efficiency and high velocity processing



Inner and outer liner articles



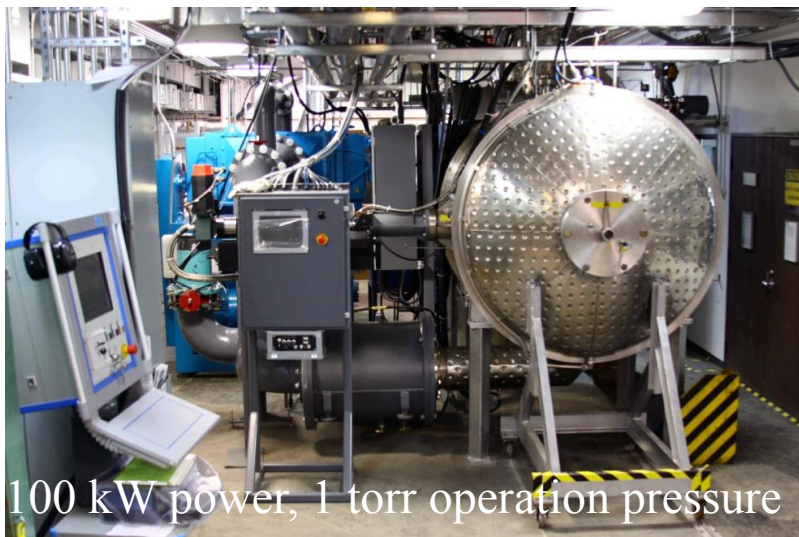
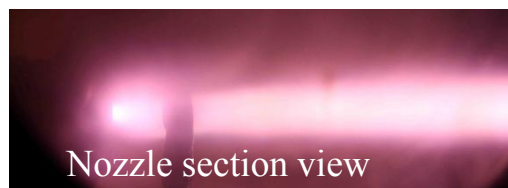
EBC coated SiC/SiC CMC Inner and Outer Liner components



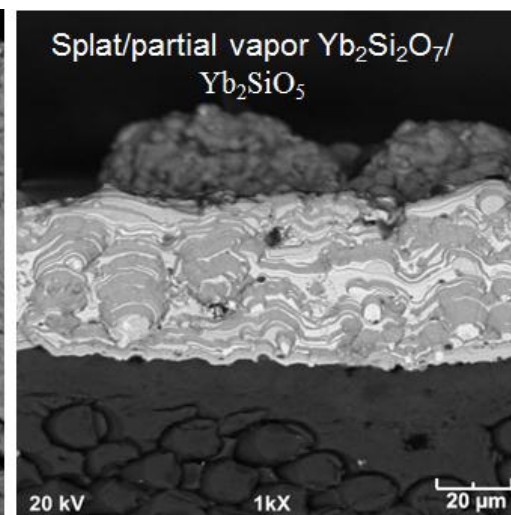
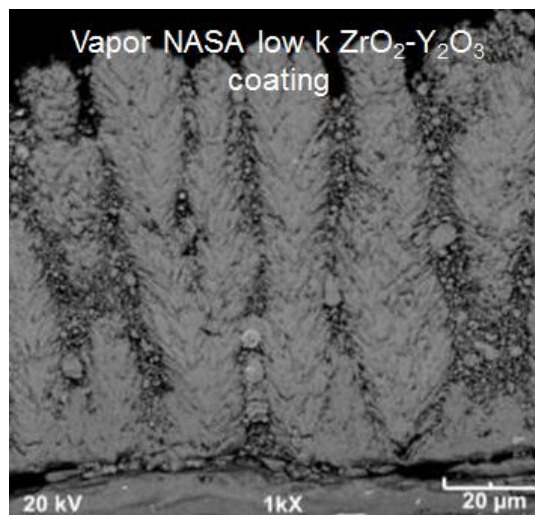


# Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

- NASA PS-PVD and PS-TF coating processing using Sulzer newly developed technology
  - High flexibility coating processing – PVD - splat coating processing at low pressure (at ~1 torr)
  - High velocity vapor, non line-of-sight coating processing for complex-shape components
  - Emphasis on fundamental process and powder composition developments for EBC depositions



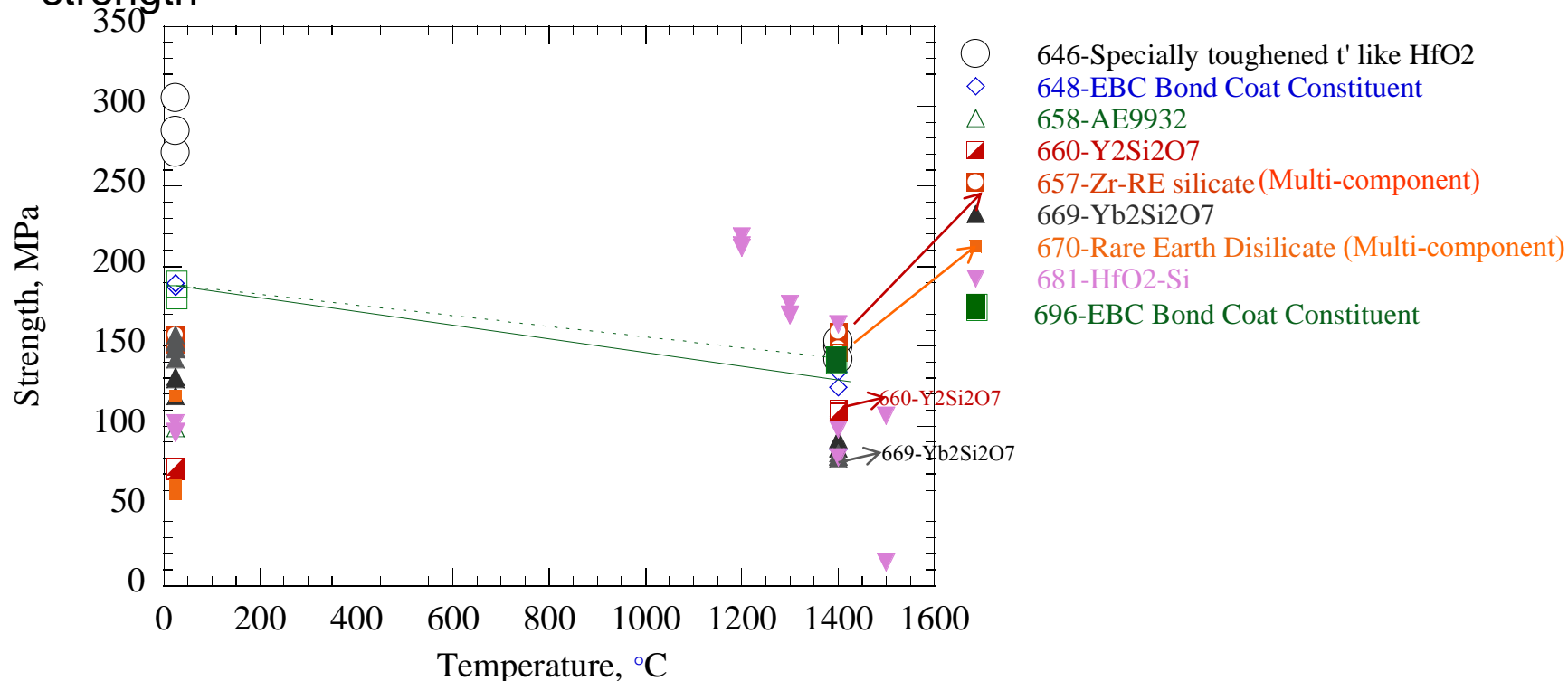
NASA hybrid PS-PVD coater system



Processed coating systems

## Advanced EBC Coating Material Strength Evaluations

- EBC and bond coat constituents are designed with high strength and high toughness to improve coating durability
  - Advanced EBC 150-200 MPa strength achieved at high temperature
  - Multicomponent silicates showed excellent high temperature properties
  - Toughness 3-4 MPa m<sup>1/2</sup> also achieved (tested at room temperature)
- HfO<sub>2</sub>-Si based systems showed promising strength and toughness
- More advanced bond coats showed higher temperature capabilities and improved strength



# NASA EBC Bond Coats for Airfoil and Combustor EBCs

– Patent Application 13/923,450 PCT/US13/46946, 2012



- Advanced systems developed and to improve Technology Readiness Levels (TRL)
- Composition ranges studied mostly from 50 – 80 atomic% silicon
  - PVD-CVD processing, for composition downselects - also helping potentially develop a low cost CVD or laser CVD approach
  - Compositions initially downselected for selected EB-PVD and APS coating composition processing
  - Viable EB-PVD and APS systems downselected and tested; development new PVD-CVD approaches

## PVD-CVD

YSi	YbGdYSi	GdYSi
ZrSi+Y	YbGdYSi	GdYSi
ZrSi+Y	YbGdYSi	GdYSi
ZrSi+Ta	YbGdYSi	GdYSi
ZrSi+Ta	YbGdSi	GdYSi-X
HfSi + Si	YbGdSi	GdYSi-X
HfSi + YSi	YbGdSi	
HfSi+Ysi+Si YbSi	YbGdSi YbGdSi YbSi	
HfSi + YbSi		
GdYbSi(Hf)		
YYbGdSi(Hf)	YbYSi YbHfSi YbHfSi YbHfSi YbHfSi YbHfSi YbSi	

## EB-PVD

HfO<sub>2</sub>-Si;  
REHfSi  
GdYSi  
GdYbSi  
NdYSi

## APS\*

HfO<sub>2</sub>-Si  
YSi+RESilicate  
YSi+Hf-RESilicate

Hf-RESilicate

Hf-RE-Al-Silicate

APS\*: or plasma spray related processing methods

## FurnaceLaser/C VD/PVD

REHfSi

Used in ERA components as part of bond coat system

Used also in ERA components  
Used in ERA components as part of bond coat system

Process and composition transitions

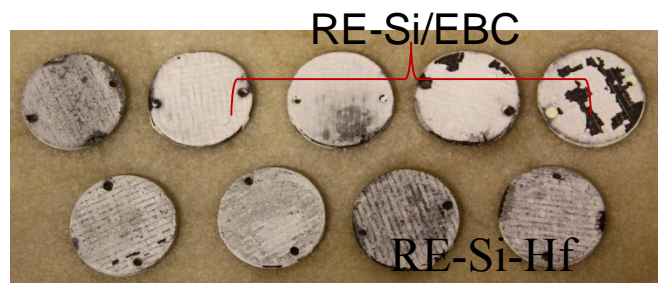


# NASA EBC Bond Coats for Airfoil and Combustor EBCs

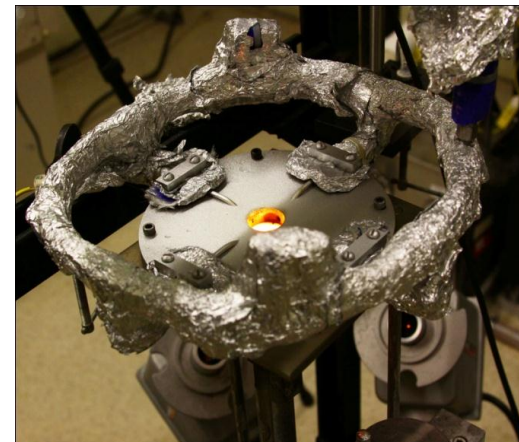
– Patent Application 13/923,450 PCT/US13/46946, 2012

**Continued**

- 1500°C (2700°F) capable RESiO+X(Ta, Al, Hf, Zr ...) EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- The bond coat systems demonstrated durability in the laser high heat flux rig in air and steam thermal gradient cyclic testing
- The bond coatings also tested in thermal gradient mechanical fatigue and creep rupture conditions



**Processed Subelement**



Steam heat flux test rig of the bond coat

Selected  
Composition Design  
of Experiment  
Furnace Cyclic Test  
Series 1500°C, in air,  
Demonstrated 500hr  
durability



Laser high heat flux cyclic rig tested Zr/Hf-RE-Si series EBC bond coats on the bond coated woven SiC/SiC CMCs at 1450°C in air and full steam environments

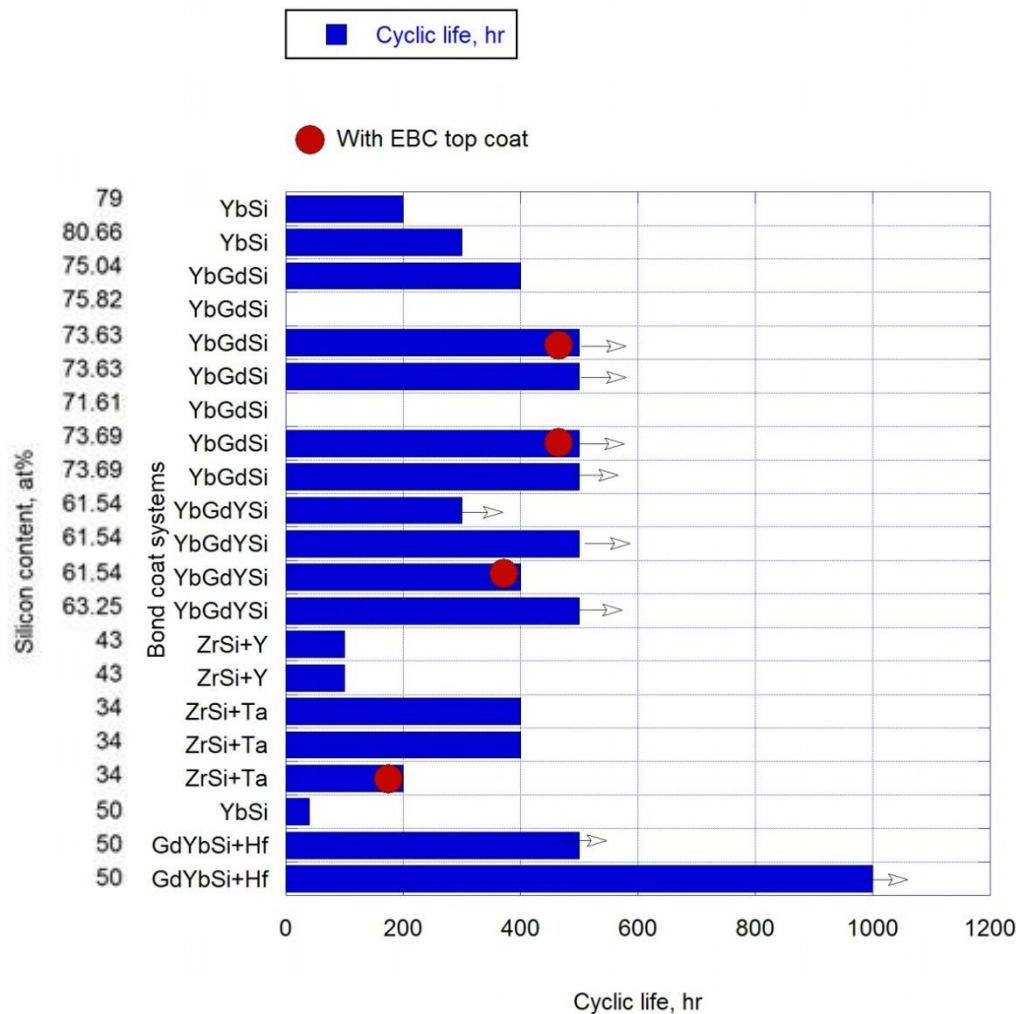


# Furnace Cycle Test Results of Selected RESi and ZrSi + Dopant Bond Coats

## - Testing in Air at 1500°C, 1 hr cycles

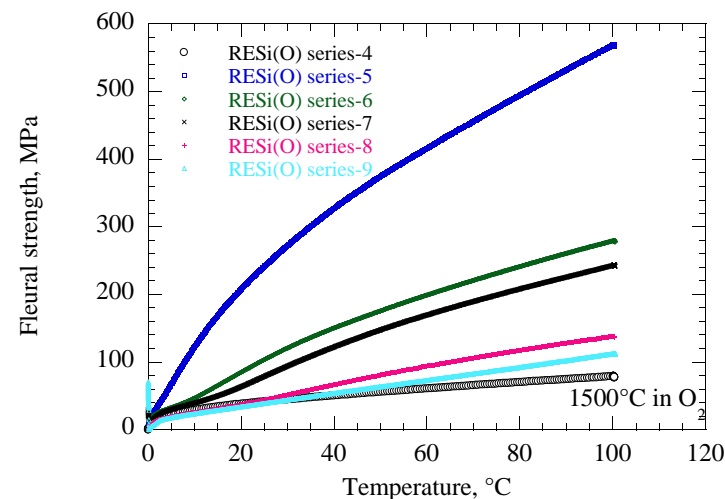
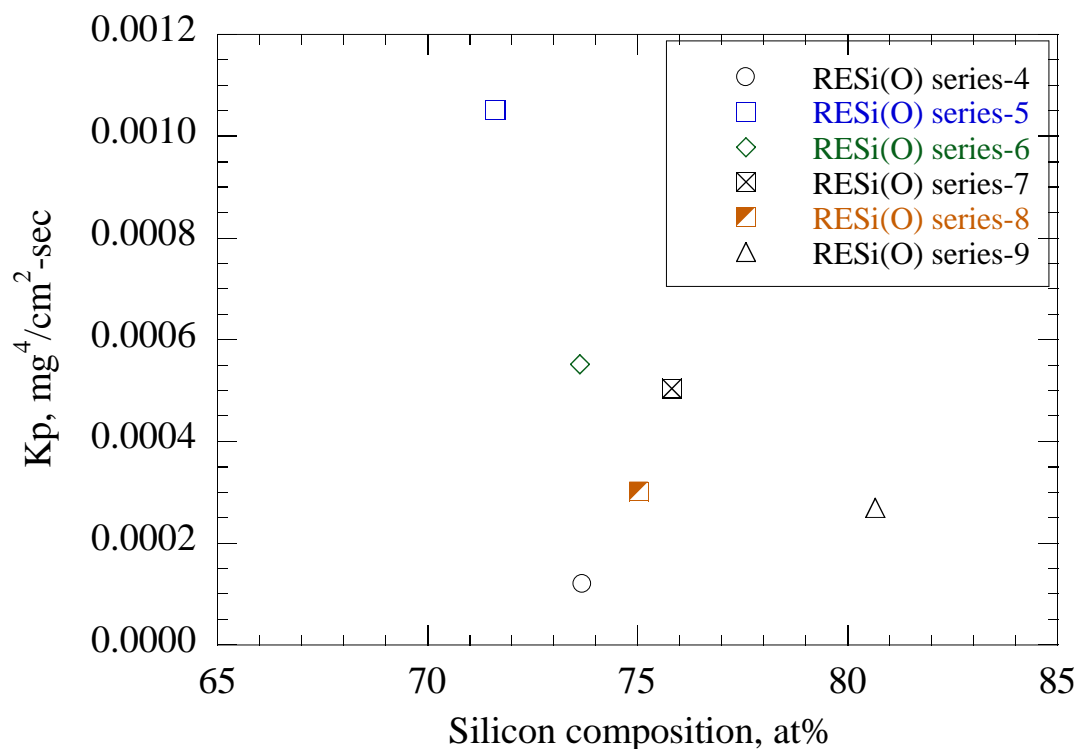


- Multi-component systems showed excellent furnace cyclic durability at 1500°C

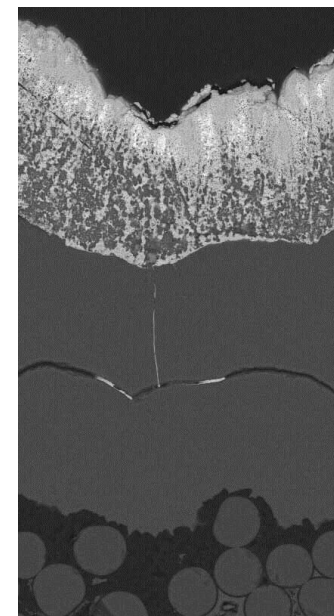


# Advanced Bond Coats for Turbine Airfoil and Combustor EBCs Developed - Continued

- 1500°C (2700°F) capable RESiO+X(Ta, Al, Hf, Zr ...) EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- Oxidation kinetics studied using TGA in flowing O<sub>2</sub>
- Parabolic or pseudo-parabolic oxidation behavior observed



An oxidized bond coat after 1500°C 100 h creep testing

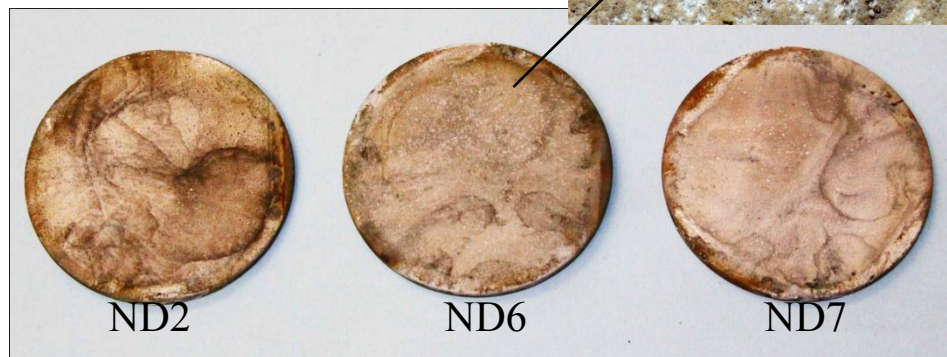
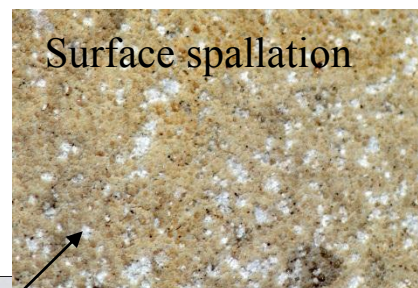
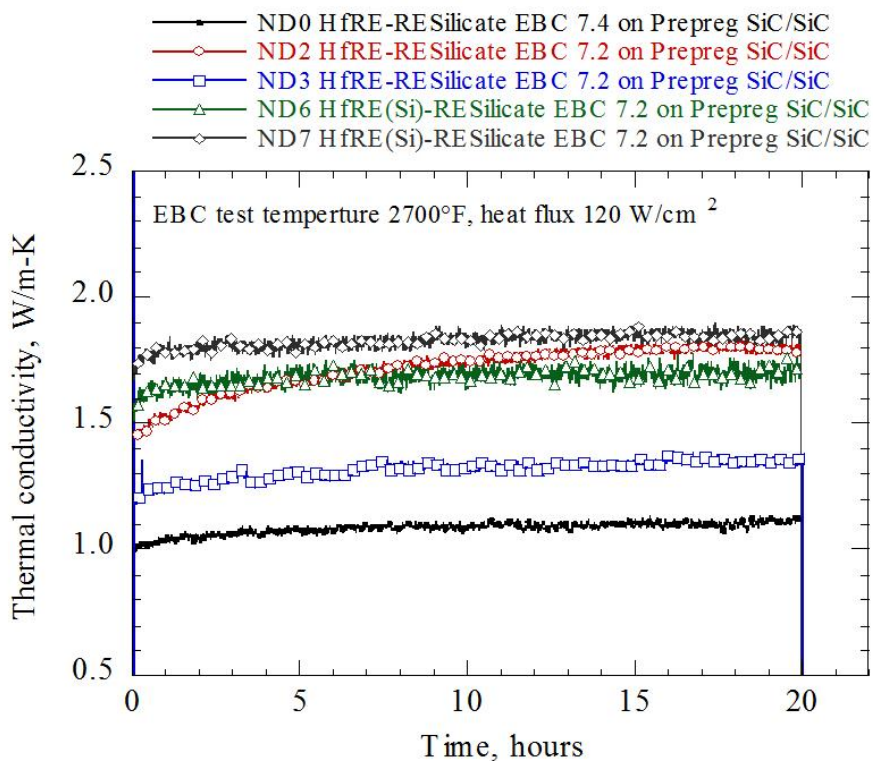


## Advanced EBC developments – Some Hybrid APS-PVD Systems and Qualification Tests

- EB-PVD  $\text{HfO}_2\text{-RE}_2\text{O}_3$  (Silicate) top coat EBC with plasma-sprayed multi-component advanced silicate sublayer EBC/ $\text{HfO}_2\text{-Si}$  bond coat systems
- Low thermal conductivity ranging 1.0 - 1.7 W/m-K
- Demonstrated high pressure environmental stability at 2600-2650°F, 12-20 atm in the high pressure burner rig



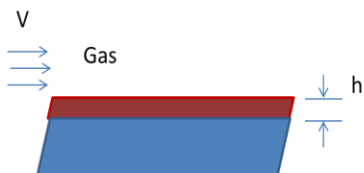
2" diameter ND3 EBC/SiC/SiC specimen after testing in the high pressure burner rig At 2600°F



High pressure burner rig tested new ND series Hybrid EBC systems coated on 2" diameter Gen II Prepreg SiC/SiC CMCs

# Understanding High Velocity Gas Flow Interactions – Columnar Structure and Toughness Considerations

- High velocity, high pressure gas impingements and shear force induced erosion in turbine engine flow condition can be of concern for low toughness coating systems
- High toughness, optimum coating density and architectures are required for durability



Shear Stress

$$\tau = \frac{F}{A} = C_D \left( \frac{1}{2} \rho V^2 \right)$$

F Shear Force

A area

$C_D$  drag coefficient

$\rho$  density

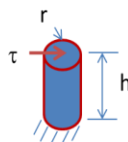
V velocity

For Ideal Gas:

$$\rho = \frac{P}{RT}$$

$$\tau = C_D \left( \frac{1}{2} \frac{P}{RT} V^2 \right)$$

If the coating is formed from columnar structures:



Bending stress at the base

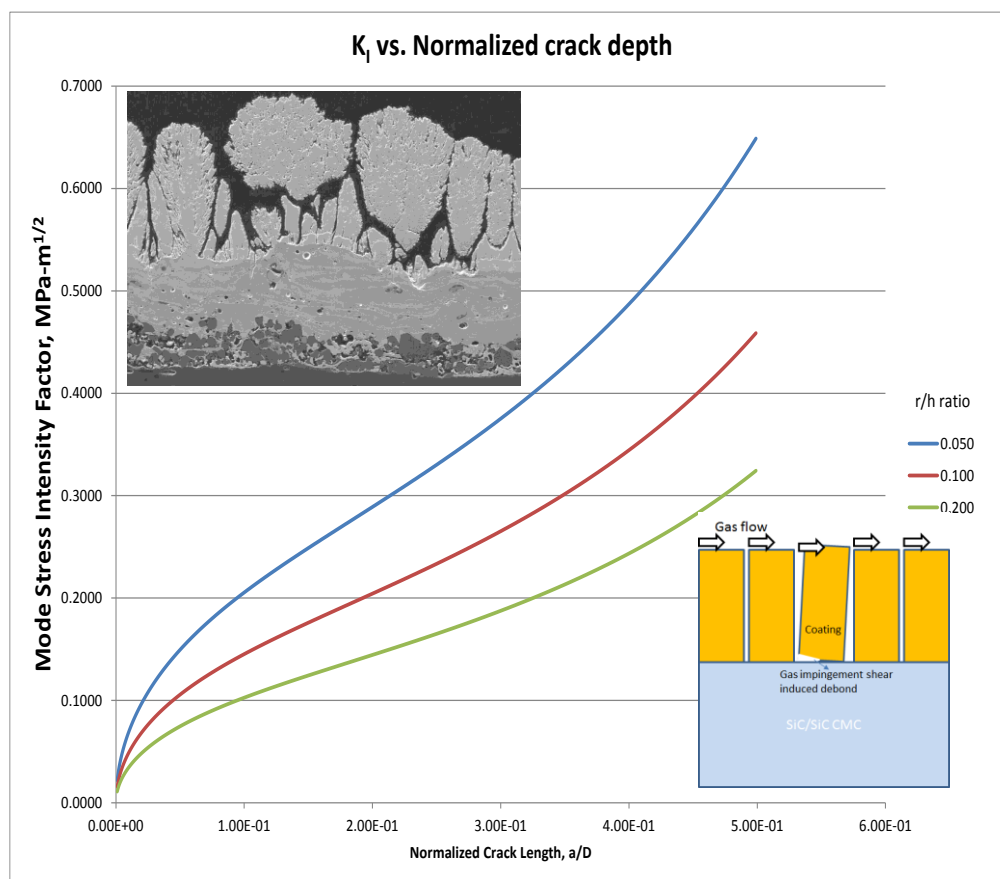
$$\sigma = \frac{M c}{I} = \frac{\tau \pi r^2 h r}{\left( \frac{\pi r^4}{4} \right)} = \frac{4 \tau h}{r}$$

$$\sigma = \frac{4 h}{r} \left( C_D \frac{P V^2}{2 R T} \right) = \frac{2 h}{r} \left( C_D \frac{P V^2}{R T} \right)$$

For a columnar structure with defect of size a

$$K_I = \sigma \sqrt{\pi a} f(a, r)$$

$$K_I = \frac{2 h}{r} \left( C_D \frac{P V^2}{R T} \right) \sqrt{\pi a} f(a, r)$$



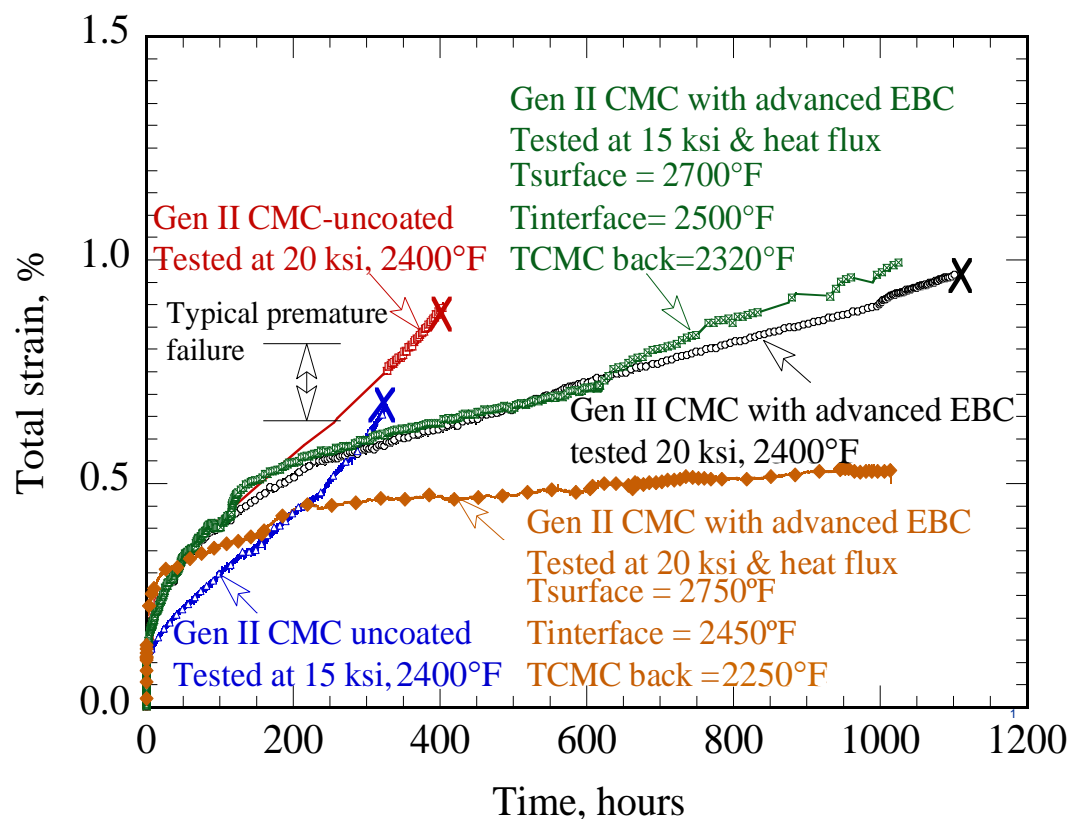
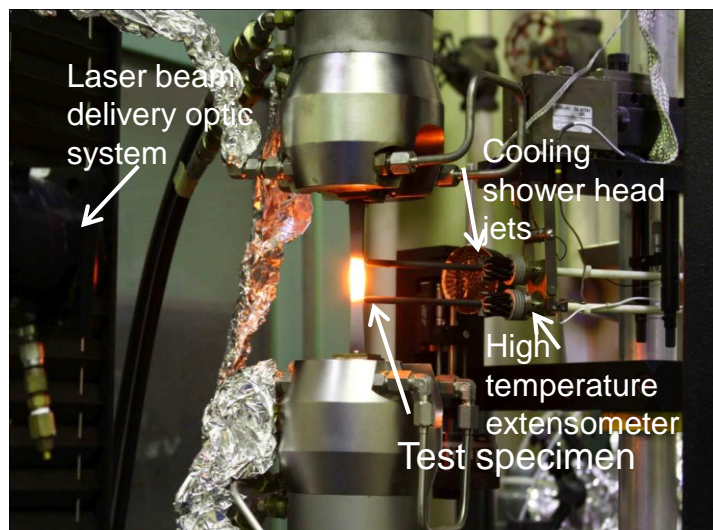
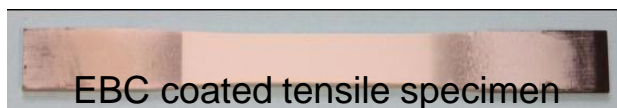
## Modeled parameters

Drag Coefficient	$C_D$		0.4
Pressure	P, psi	750	5171068 Pa
Velocity	V		1200 m/sec
Temperature	T, F	3000	1921.039 K
Gas Constant	R		461.5 J/Kg/K
Column Height	h		0.0002 m
Column Radius	r		0.00001 m
Stress			1.34E+08 Pa



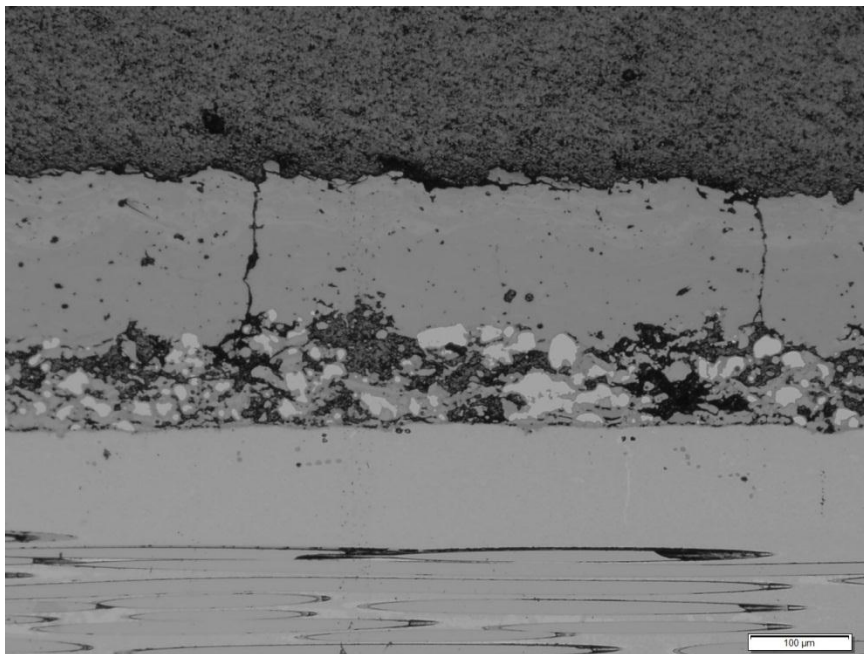
## Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- Advanced high stability multi-component hafnia-rare earth silicate based turbine environmental barrier coatings being successfully tested for 1000 hr creep rupture
- EBC-CMC creep, fatigue and environmental interaction is being emphasized

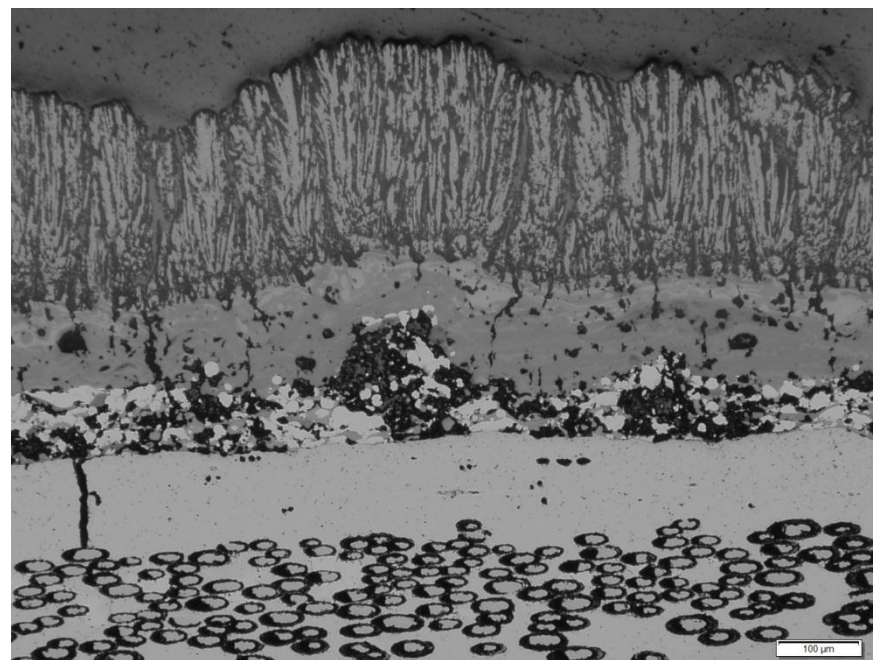


# Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

- Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at  $T_{\text{EBC}}$  2700°F,  $T_{\text{CMC interface}} \sim 2500^\circ\text{F}$
- The  $\text{HfO}_2$ -Si bond coat showed excellent durability



EBCs on Gen II CMC after 1000 hr fatigue testing

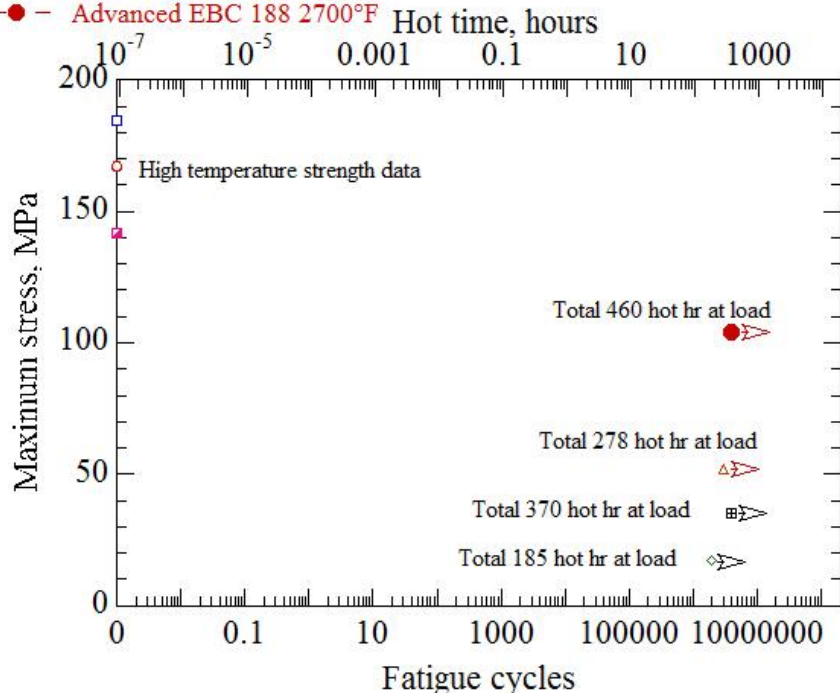
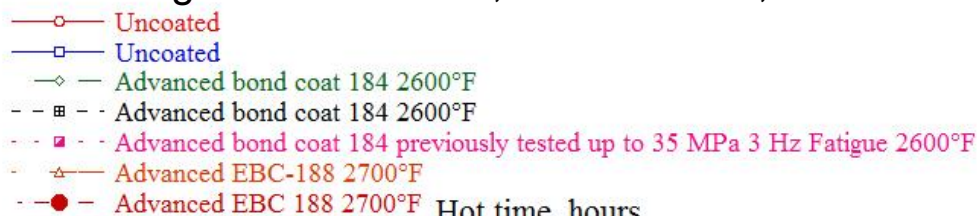


Hybrid EBCs on Gen II CMC after 100 hr low cycle creep fatigue testing



## Fatigue Tests of Advanced RESi Bond Coats and EBC Systems

- Uncoated CMCs, Bond coat/CMC and EBC/Bond Coat/CMC systems tested flexural fatigue tests with 15 Ksi loading
- Heating provided by steady-state laser
- Strength and Fatigue cycles tested
- Fatigue tests at 3 Hz, 2600-2700°F, stress ratio 0.05, surface tension-tension cycles

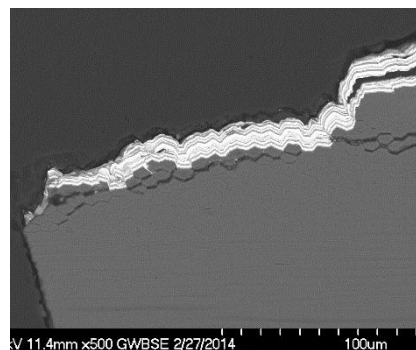


Tested, SA Tyrannohex with bond coat only

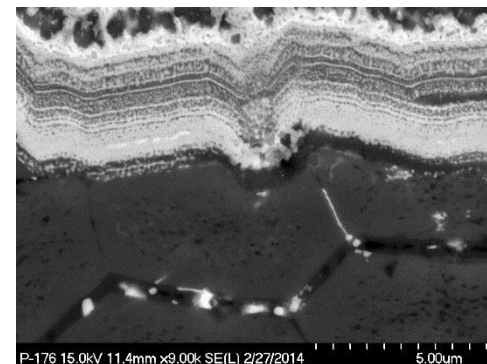


Tested, SA Tyrannohex with EBC system 188

Achieved long-term fatigue lives  
(near 500 hr) with EBC at 2700°F



Tested specimen cross-sections



P-176 15.0kV 11.4mm x9.00k SE(L) 2/27/2014

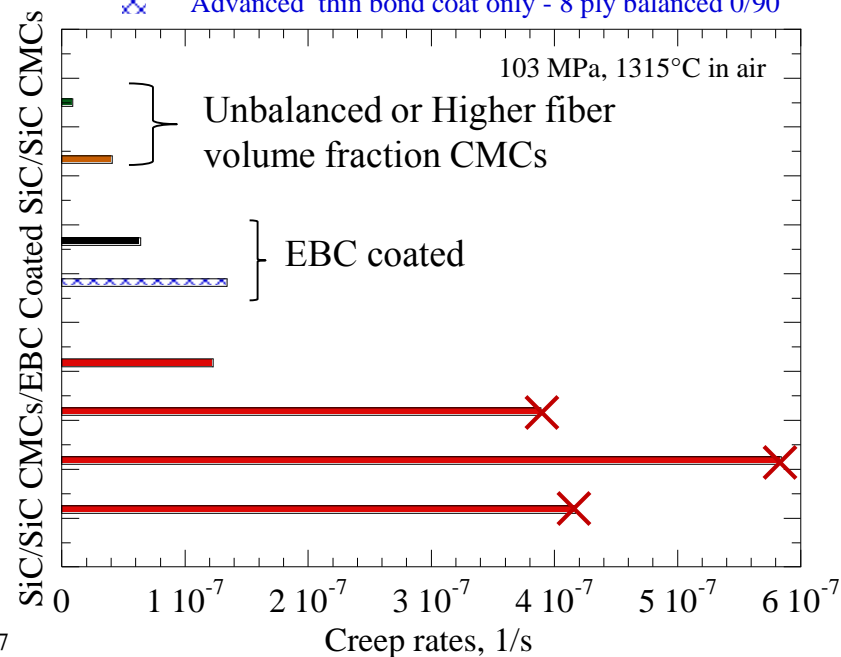
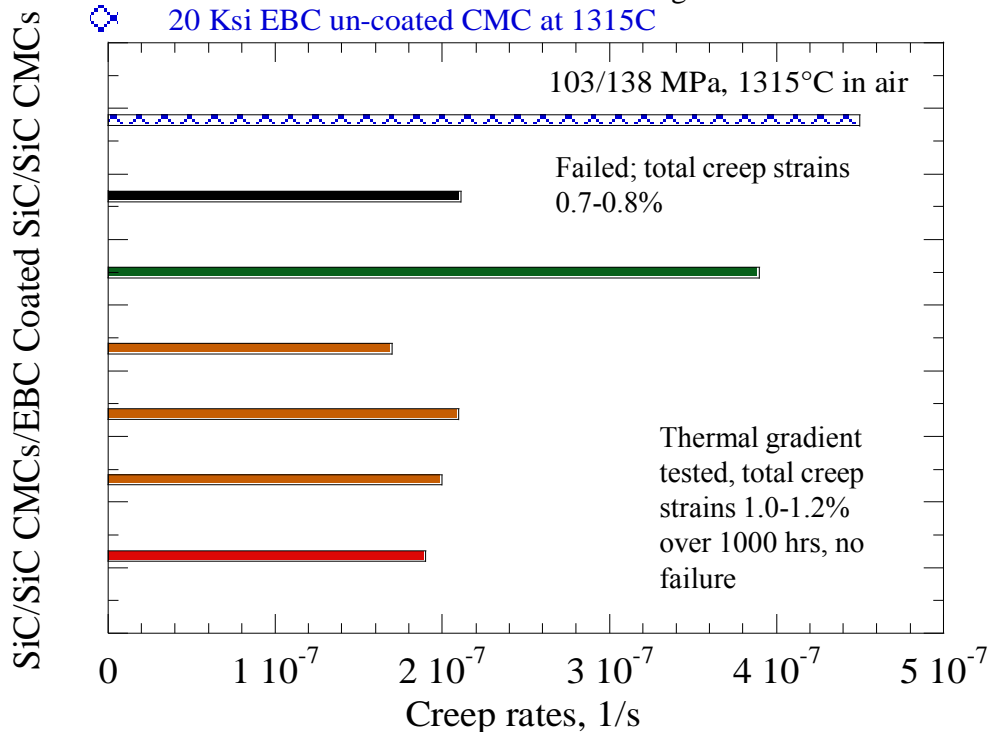
# Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

- Effects of temperature, load, heat flux and environments (steam and combustion air) for coated SiC/SiC CMC are being investigated
- EBC coated CMCs showed improved durability

- 15 Ksi, thermal gradient\_EBC coated CMC (TCMC average 1315C)
- 20 Ksi, thermal gradient\_EBC coated CMC (TCMC average 1315C)

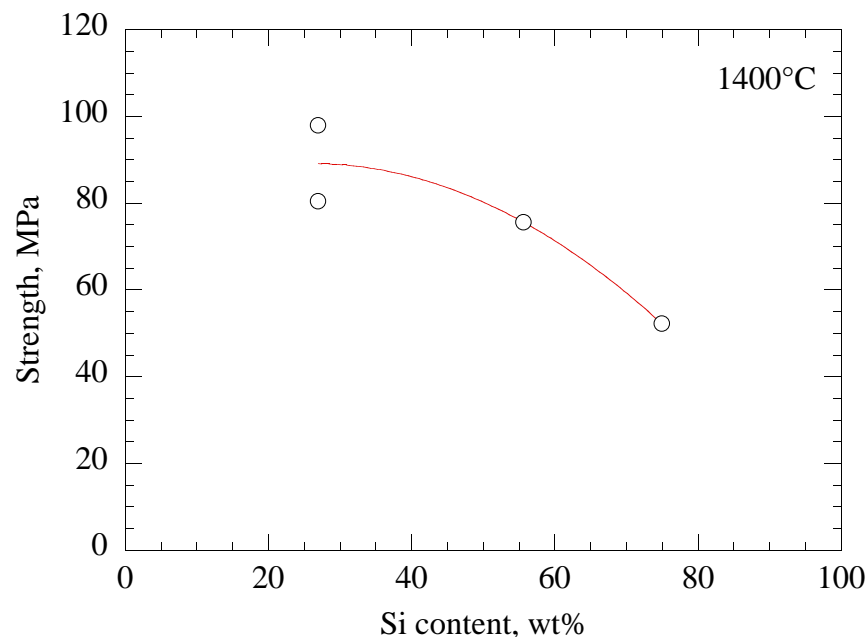
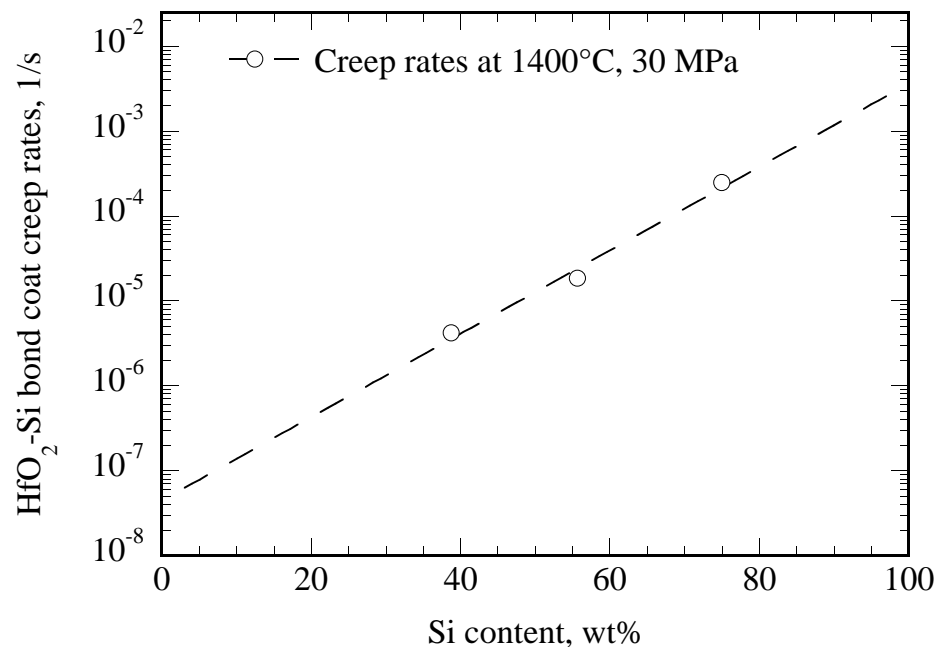
- 20 Ksi EBC coated CMC at 1315C
- 20 Ksi EBC coated CMC at 1315C Fatigue maximum stress 20 Ksi
- 20 Ksi EBC un-coated CMC at 1315C

- Gen II MI SiC/SiC 8 Ply balanced 0/90
- Gen II MI SiC/SiC 6 ply unbalanced 0/90
- CVI Woven SiC/SiC
- Advance EBC system coated 8 ply balanced 0/90
- Advanced thin bond coat only - 8 ply balanced 0/90



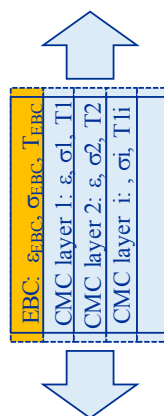
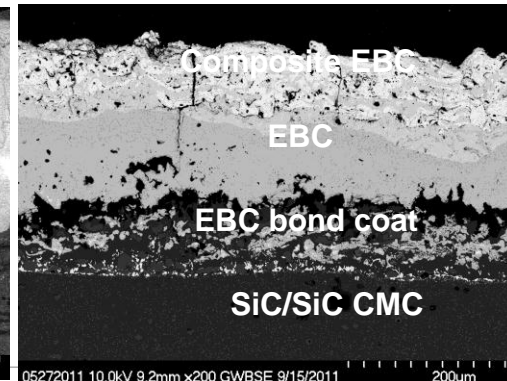
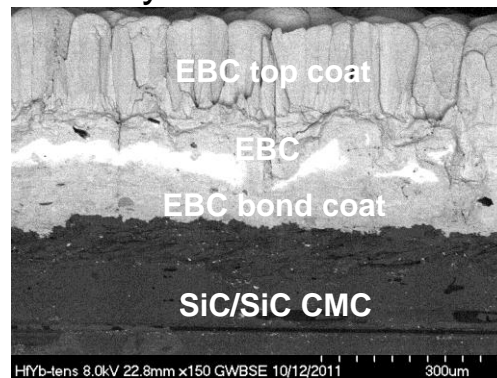
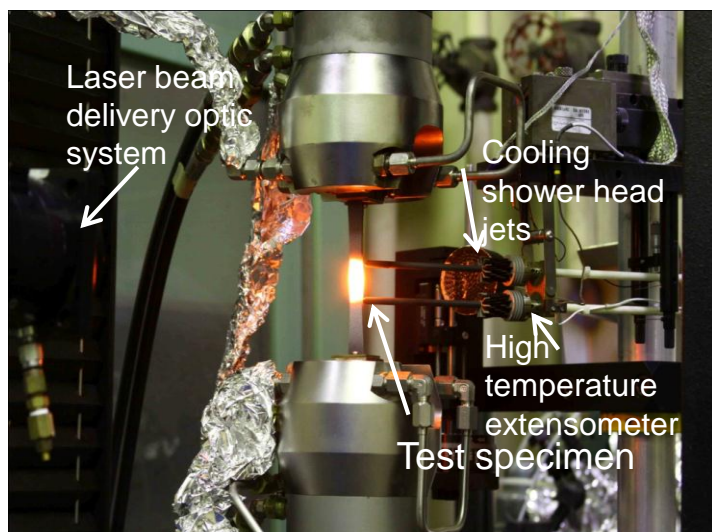
# Advanced HfO<sub>2</sub>-Si Bond Coats: Effects of Compositions on Strength and Creep Rates

- The HfO<sub>2</sub>-Si composite coatings showed high strength, and improved creep resistance at high temperatures
- Increased HfO<sub>2</sub>-HfSiO<sub>4</sub> contents improve high temperature strength and creep resistance

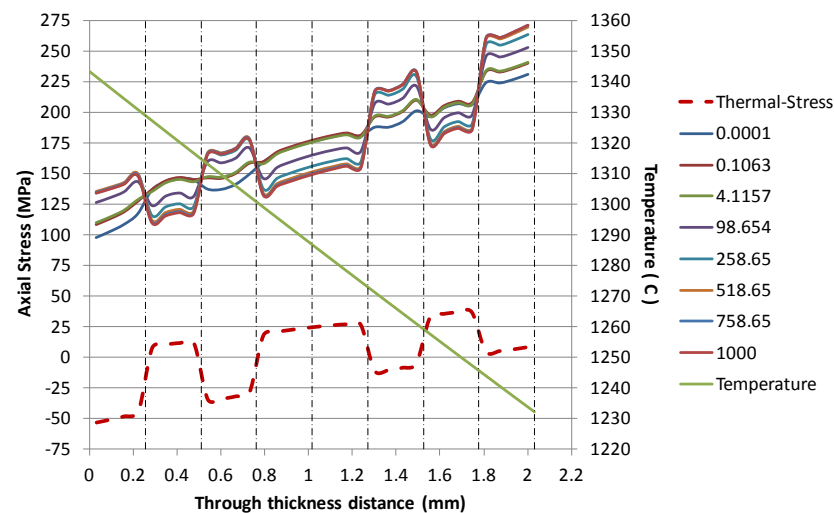


# EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling

- An equivalent stress model is established for EBC multicrack stress intensity modeling: emphasize creep, thermal gradient and stress rupture interactions
- Benchmark failure modes established in EBC systems



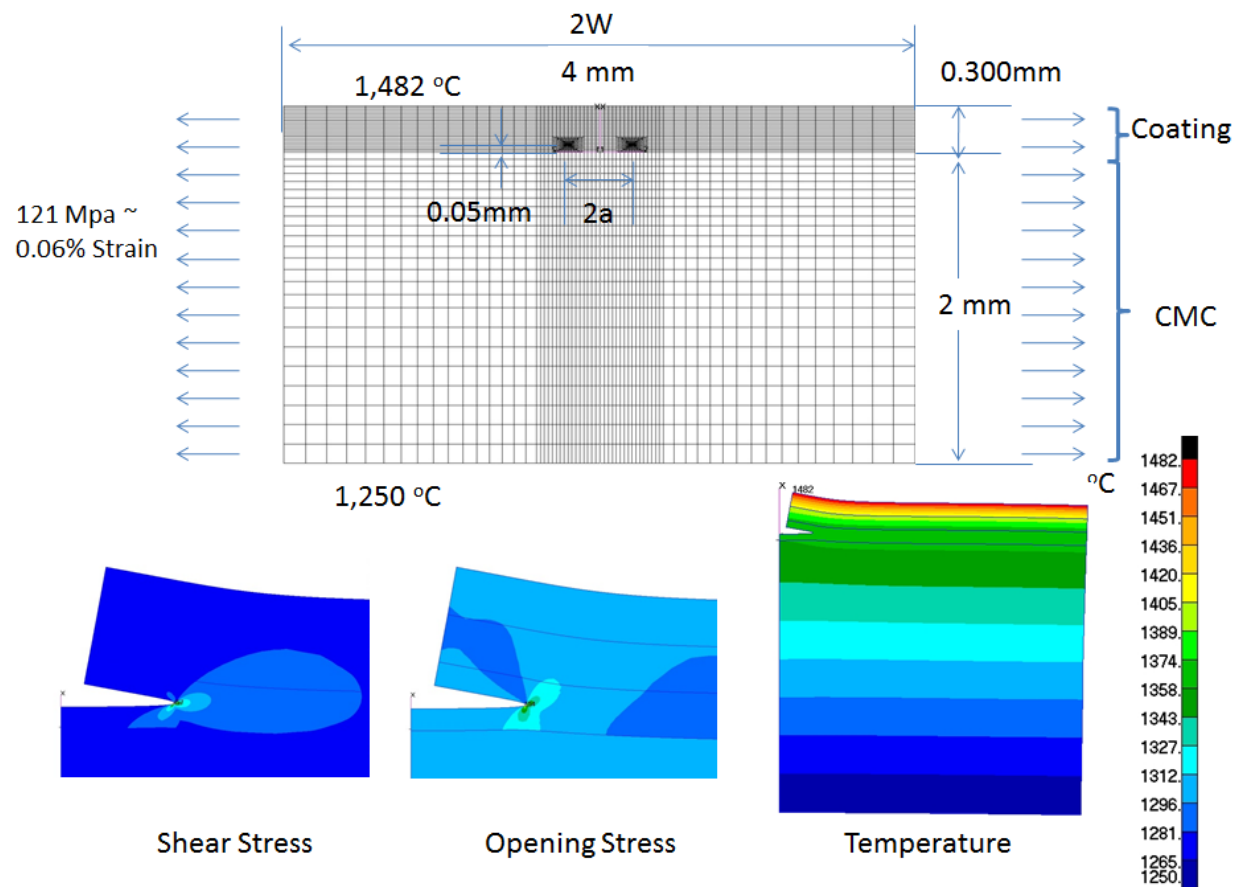
Through the thickness axial stress profile at different time



Stress gradients in Prepreg SiC/SiC CMC substrates under thermal gradient + mechanical creep loading

## EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling - Continued

- An equivalent stress model is established for EBC multicrack stress intensity modeling: emphasize creep, thermal gradient and stress rupture interactions
- Benchmark failure modes established in EBC systems

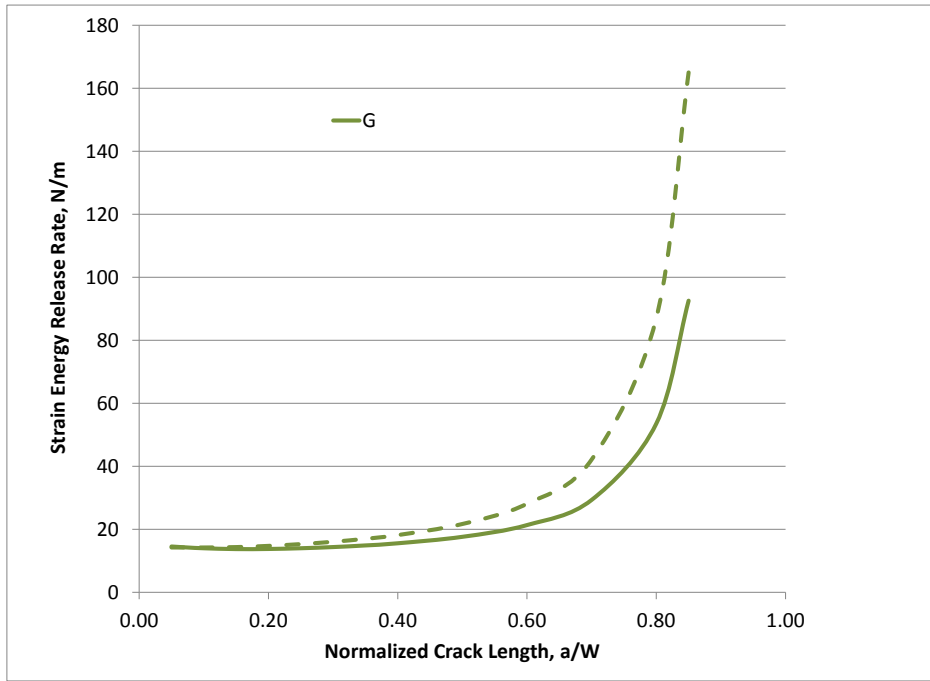
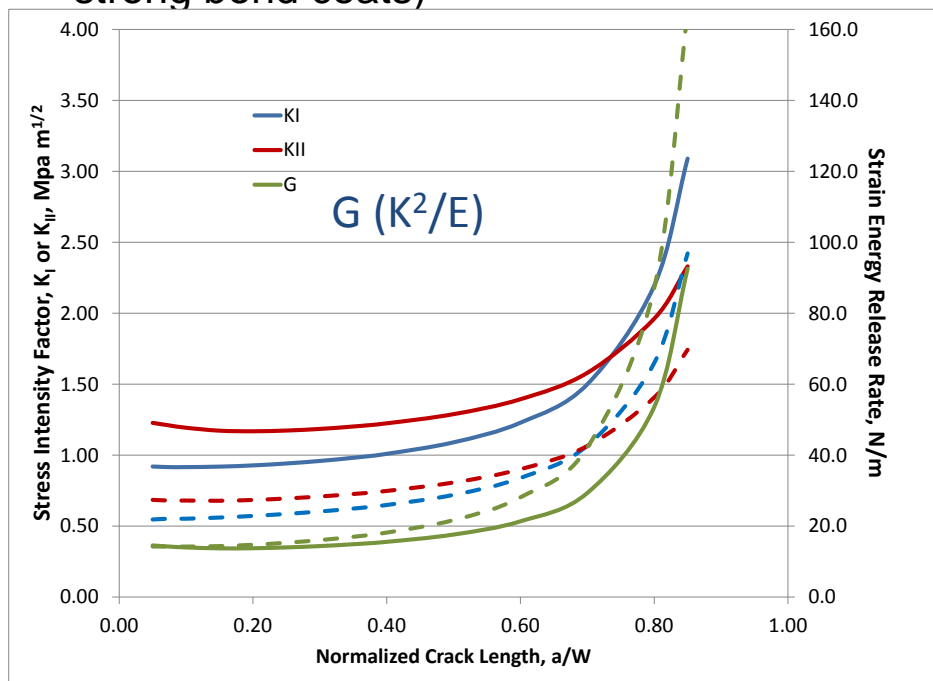


Finite Element Analysis (FEA) Modeling

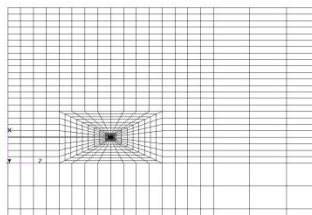


# EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling – Bond Coat Stiffness Effect

- Delamination driving forces: uniform remote applied stress case, 0.300 mm thickness coating with  $\sim 0.06\%$  total strain
- Effect of bond coat elastic modulus:  $E=150$  GPa vs.  $E=50$  GPa
- Strong bond coats expected to have less creep damage (lower strain energy release rate  $G$  for strong bond coats)



Solid Lines-strong bond coat  
 $E=150$  GPa EBC  
 $E=150$  GPa bond coat



$E=150$  GPa

$E=50$  GPa

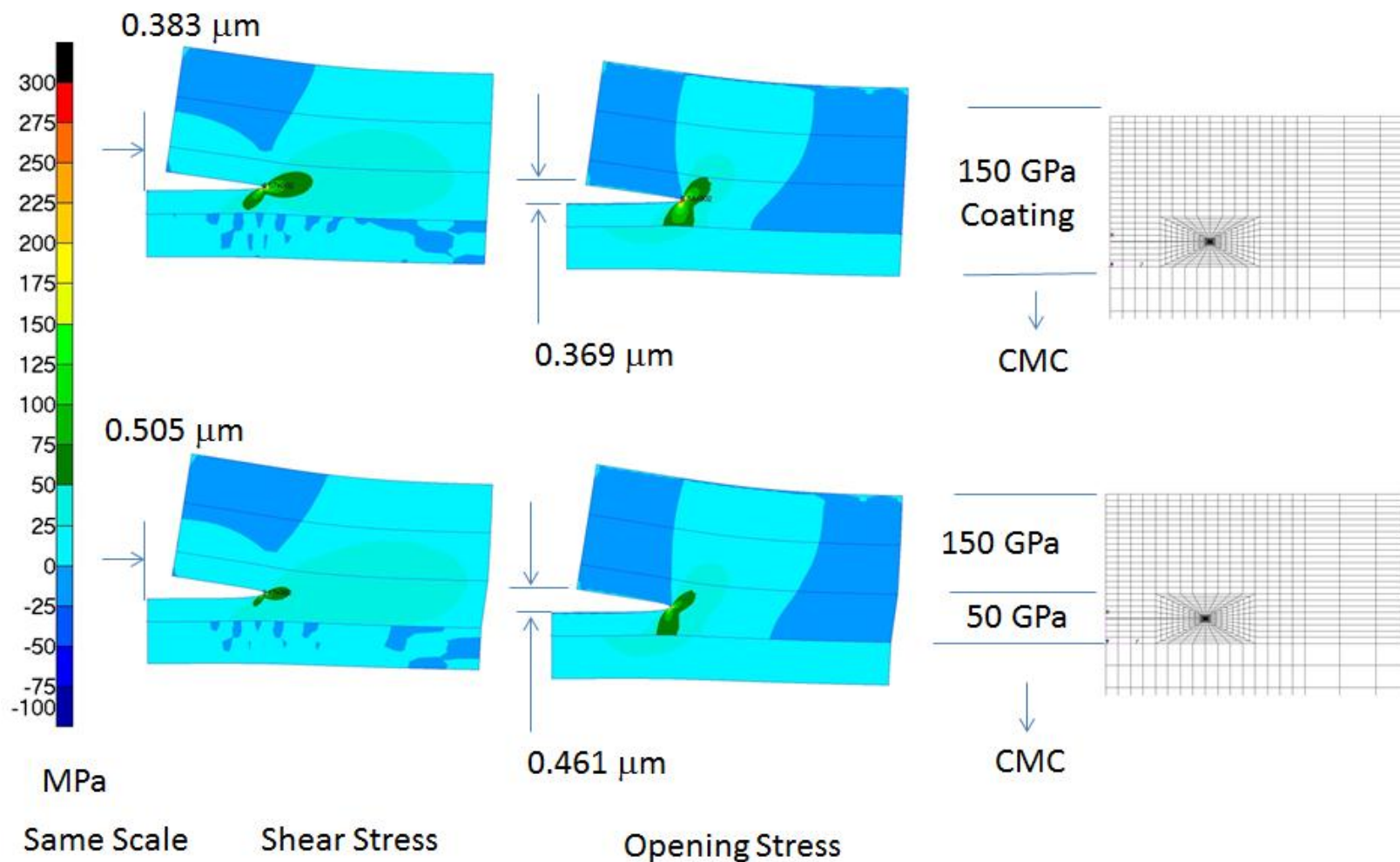


Dashed Lines: Soft bond coat



## EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling – Bond Coat Stiffness Effect

- Advanced EBCs designed with higher strength and stiffness to improve creep, fatigue, and cyclic durability



## The Advanced EBC on SiC/SiC CMC Turbine Airfoils Successfully Tested for Rig Durability in NASA High Pressure Burner Rig

- NASA advanced EBC coated turbine vane subcomponents tested in rig simulated engine environments (up to 240 m/s gas velocity, 10 atm), reaching TRL of 5
- Turbine EBCs generally intact (some minor partial coating top coat spalling for the Prepreg MI SiC/SiC vane)
- Some minor CMC vane degradations after the testing



EBC Coated CVI SiC/SiC vane after 31 hour testing at 2500°F+ coating temperature



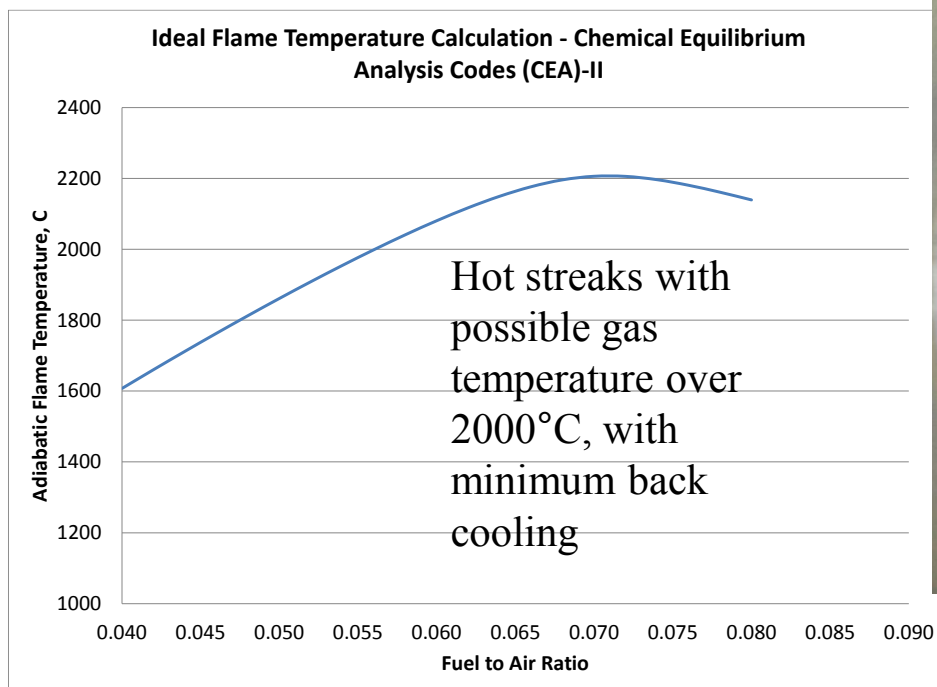
EBC Coated Prepreg SiC/SiC vane after 21 hour testing at 2500°F



EBC Coated Prepreg SiC/SiC vane tested 75 hour testing at 2650°F

## The EBC Coated SiC/SiC CMC Combustor Liner Successfully Demonstrated for Rig Durability in NASA High Pressure Burner Rig (First Inner Liner Processed at Sulzer with Triplex Pro)

- Tested pressures at 500 psi external for outliner, and up to 220 psi inner liners in the combustion chamber (16 atm), accumulated 250 hours in the high pressure burner rig
- Average gas temperatures at 3000°F (1650°C) based on CEA calculations, the liner EBCs tested at 2500°F (1371°C) with heat fluxes 20-35 W/cm<sup>2</sup>, and the CMC liner component at 1800-2100°F (~1000-1100°C)



Some minor coating spalling at hot streak impingement

## Summary

- **Durable EBCs are critical to emerging SiC/SiC CMC component technologies**
  - The EBC development built on a solid foundation from past experience, evolved with the current state of the art compositions of higher temperature capabilities and stabilities
    - Multicomponent EBC oxide/silicates
    - RE-Si bond coat
  - Advanced EBC processing and testing capabilities significantly improved, helping more advanced coatings to be realized for complex turbine components
  - Better understood the coating failure mechanisms, and helping developing coating property databases and life models, aiming at developing higher stability, higher strength EBC and bond coats
  - Emphasized thin coating turbine and combustor EBC coating configurations, demonstrated component EBC technologies in simulated engine environments – TRL 5



## Future Directions and Opportunities

- **High stability turbine airfoil and combustor coating system development continues to be a high priority**
  - Advanced composition development, optimization, down-select a EBC coating System(s)
  - Reduce recession rates, improve the temperature stability and complex environment resistance, such as in CMAS environments
  - Low thermal conductivity
- **Advanced environmental barrier coatings with significantly improved thermal and mechanical load capability**
  - Emphasize coating strength and toughness
  - Better understand and improve creep, fatigue, and environment interactions
  - Design and demonstrate long-term high heat flux cyclic stability
- **Materials and component system integration**
  - Develop robust and economical processing capabilities
  - Optimize and validate coatings with more complex sub-elements and components
- **Laboratory simulated high heat flux stress, environment testing and life prediction methodology development, validating model developments**



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